ELECTRICAL & COMPUTER ENGINEERING

ECE-595 Network Softwarization

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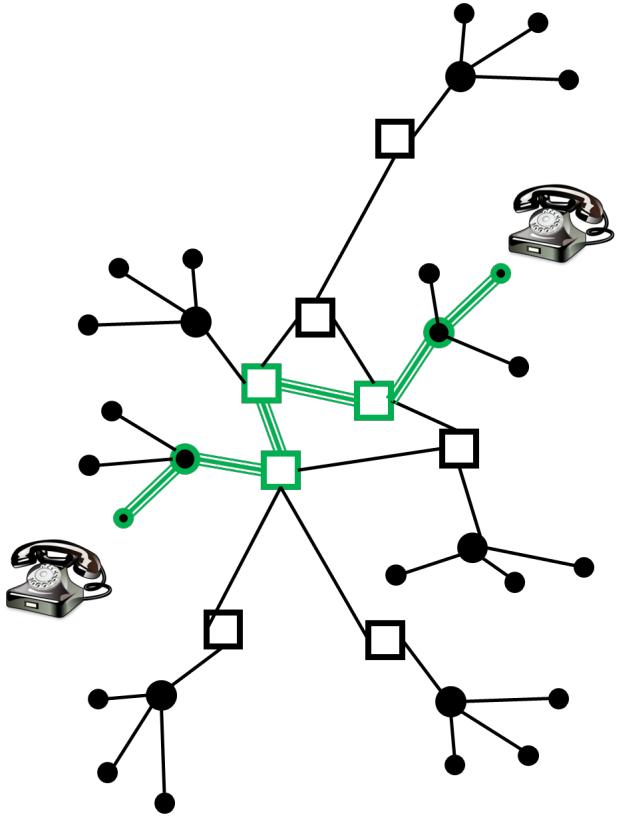
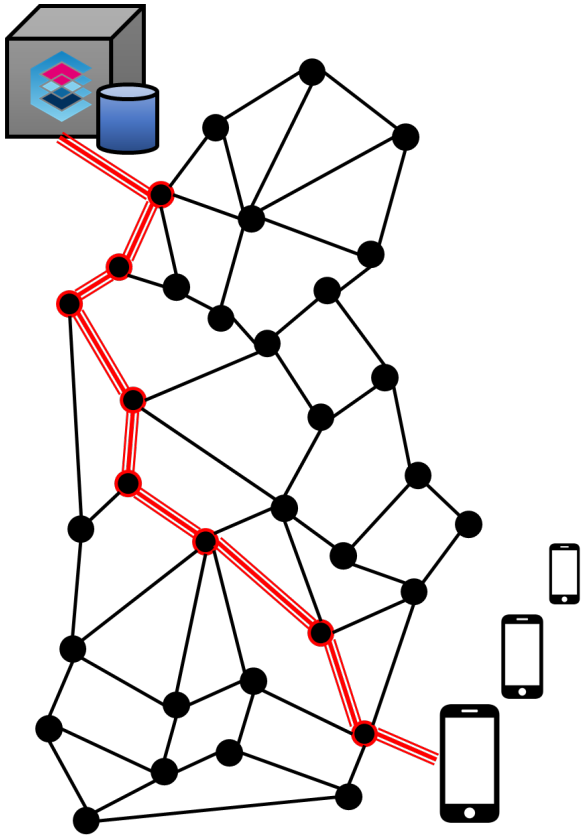
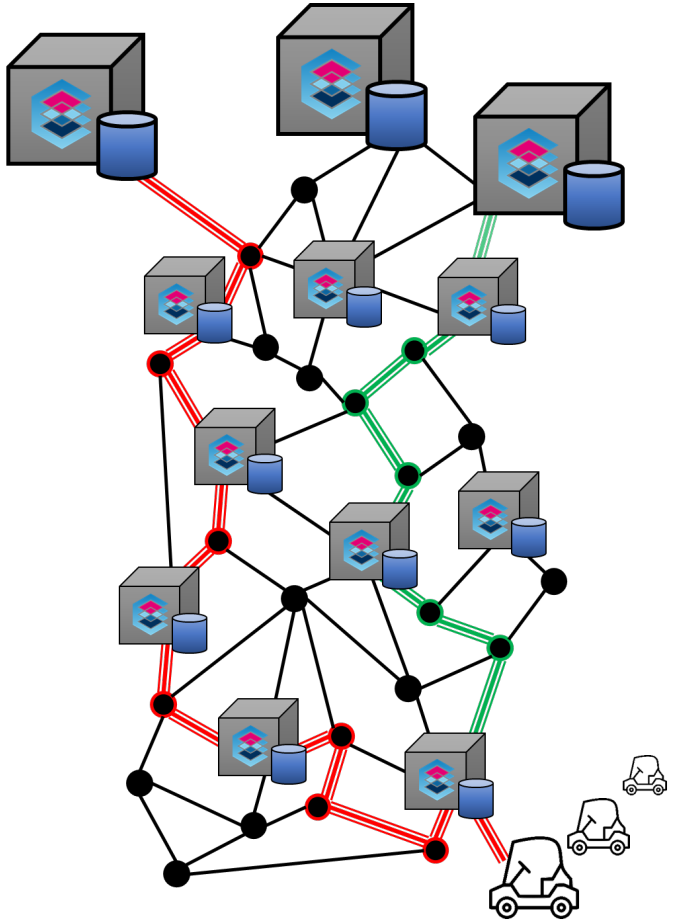
Evolution of Communication Networks



Places
Voice



People	
Voice	Data



Things		
Voice	Data	Control

On the need of Virtualization and Computing in future Communication Networks

- Motivating Virtualization & Computing in Communication Networks
- You should learn about:
  - In-network computing as a result from network operators' requests
  - In-network computing is the enabler for fast innovation roll-out
  - In-network computing is tackling the propagation delay problem
  - In-network computing can reduce the data rate by in-network operations:
    - Network coding
    - Compressed sensing
  - In–network computing can cause extra costs:
    - Energy // Price // Latency

Computing in Communication Networks

PART 1 FUTURE COMMUNICATION NETWORKS AND SYSTEMS

PART 2 CONCEPTS

PART 3 ENABLING TECHNOLOGIES

PART 4 INNOVATION TRACK

PART 5 BUILDING THE TESTBED

PART 6 EXAMPLES

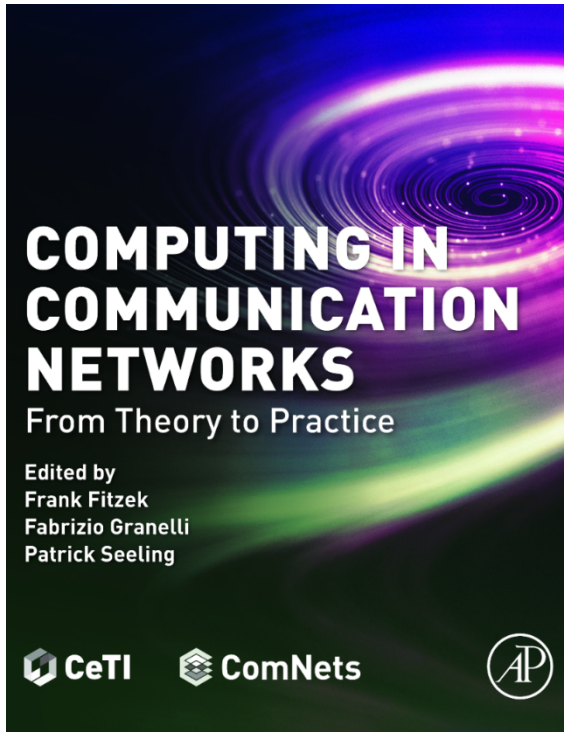
PART 7 EXTENSIONS

PART 8 TOOLS

Additional lecture videos

https://cn.ifn.et.tu-dresden.de/compcombook/

SCAN ME



Frank H. P. Fitzek; Fabrizio Granelli; Patrick Seeling
Computing in Communication Networks – From Theory to Practice
Elsevier, 2020, ISBN: 9780128204887

Further Useful Links

CompBook

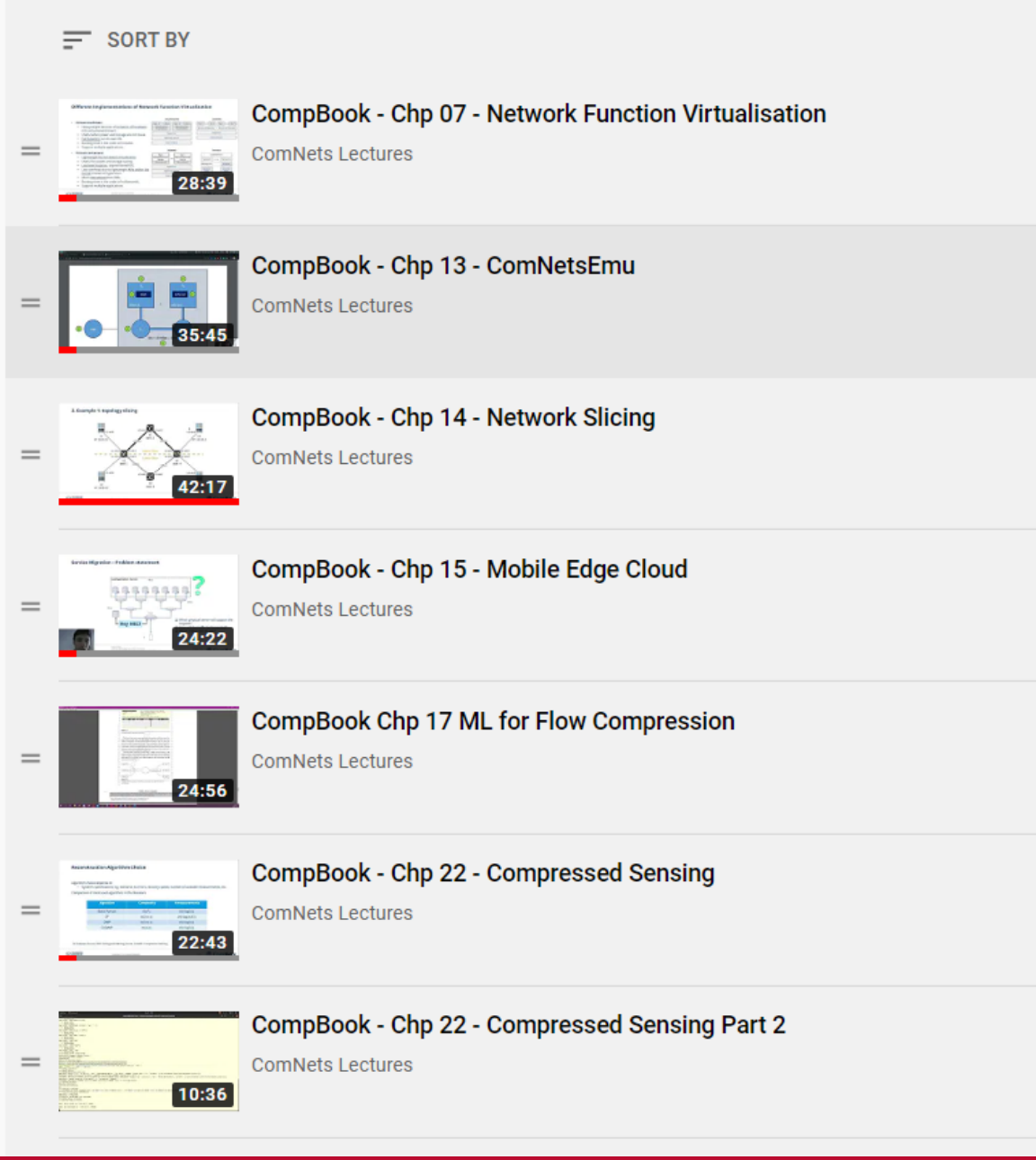
https://tinyurl.com/y8pz22bu

Network Coding

https://tinyurl.com/y9lrfqty

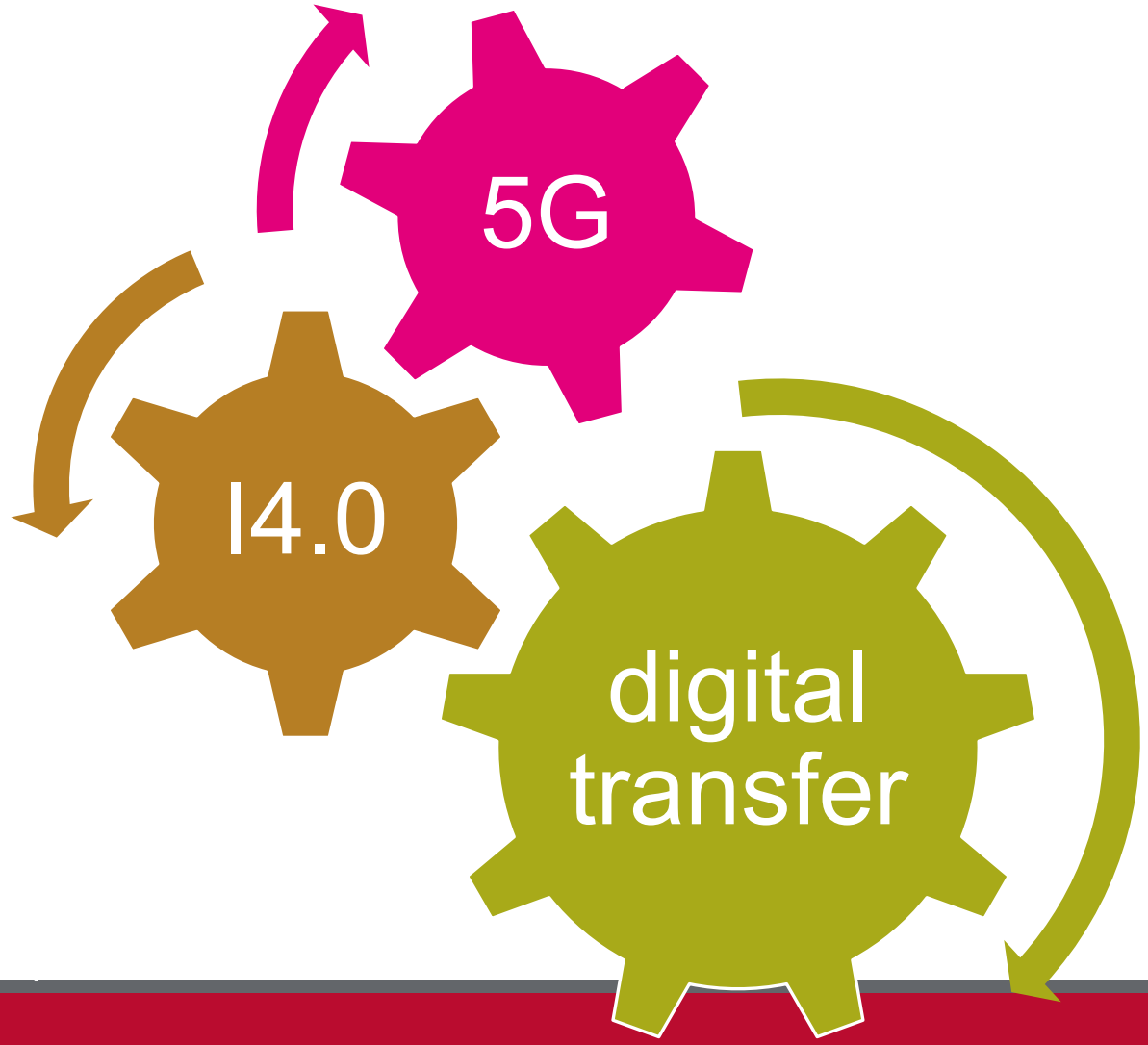
ComNets 2

https://tinyurl.com/ya5dzqny



5G Communication System & The Need for Computing

What makes 5G so important?



Computing in Communication Networks

PART 1 FUTURE COMMUNICATION NETWORKS AND SYSTEMS

- CHAPTER 1 Computing in Future Communication Networks 3
  - 1.1 Evolution of Communication Networks 4
    - 1.1.1 The Telephone Networks: Circuit-Switched 5
    - 1.1.2 The Internet: Packet-Switched 6
    - 1.1.3 The Cellular Communication Networks 8
  - 1.2 The 5G Communication System 12
    - 1.2.1 The 5G Atom Core: Use Cases 14
    - 1.2.2 First Tier: The Technical Requirements 21
    - 1.2.3 Second Tier: The Concepts 33
    - 1.2.4 Third Tier: The Softwarization Technologies . . . 43
    - 1.2.5 Fourth Tier: Innovation and Novelties 45
  - 1.3 Softwarization: The Game Changer for Network Operators 46

PART 2 CONCEPTS

PART 3 ENABLING TECHNOLOGIES

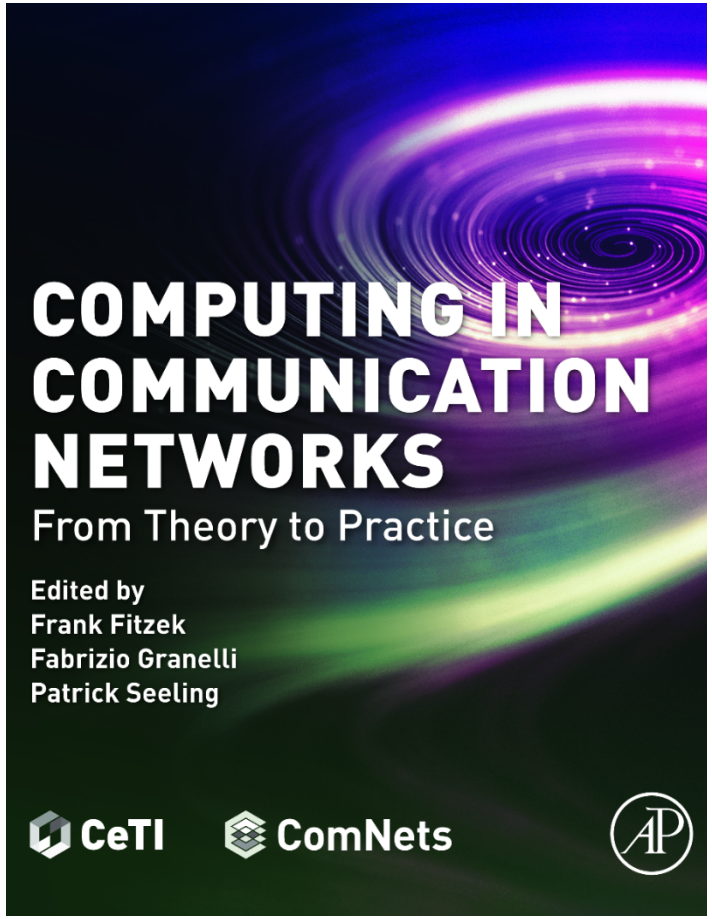
PART 4 INNOVATION TRACK

PART 5 BUILDING THE TESTBED

PART 6 EXAMPLES

PART 7 EXTENSIONS

PART 8 TOOLS



5G (r)evolution

wireless world

1G 2G 3G 4G

You don't know where you're going until you know where you've been.

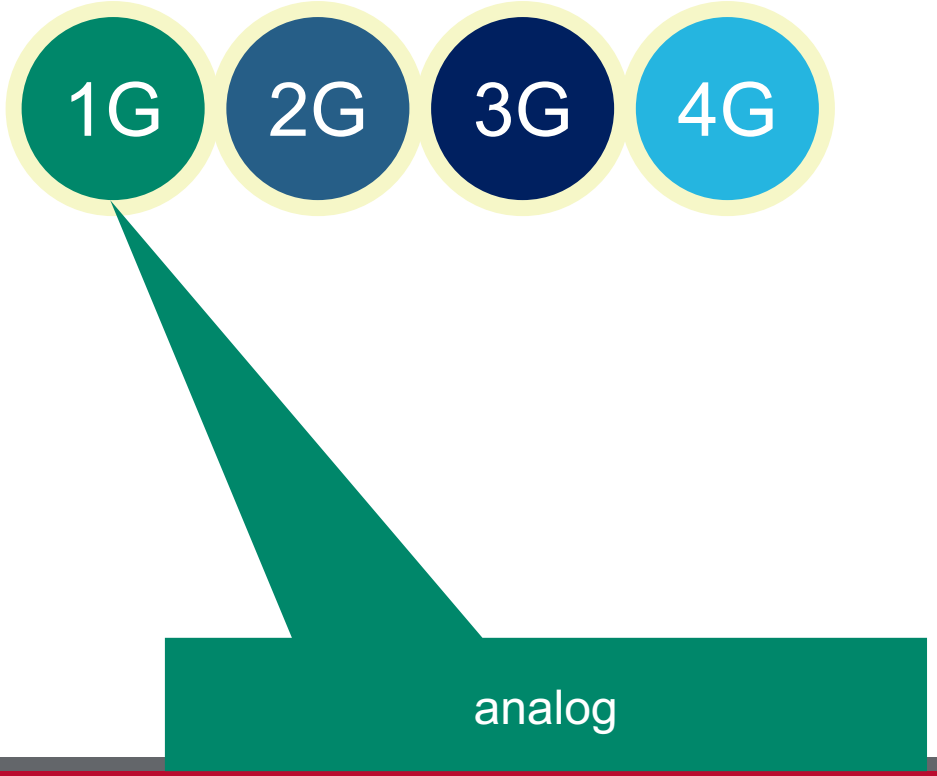
5G (r)evolution

wireless world

1G 2G 3G 4G

5G (r)evolution

wireless world



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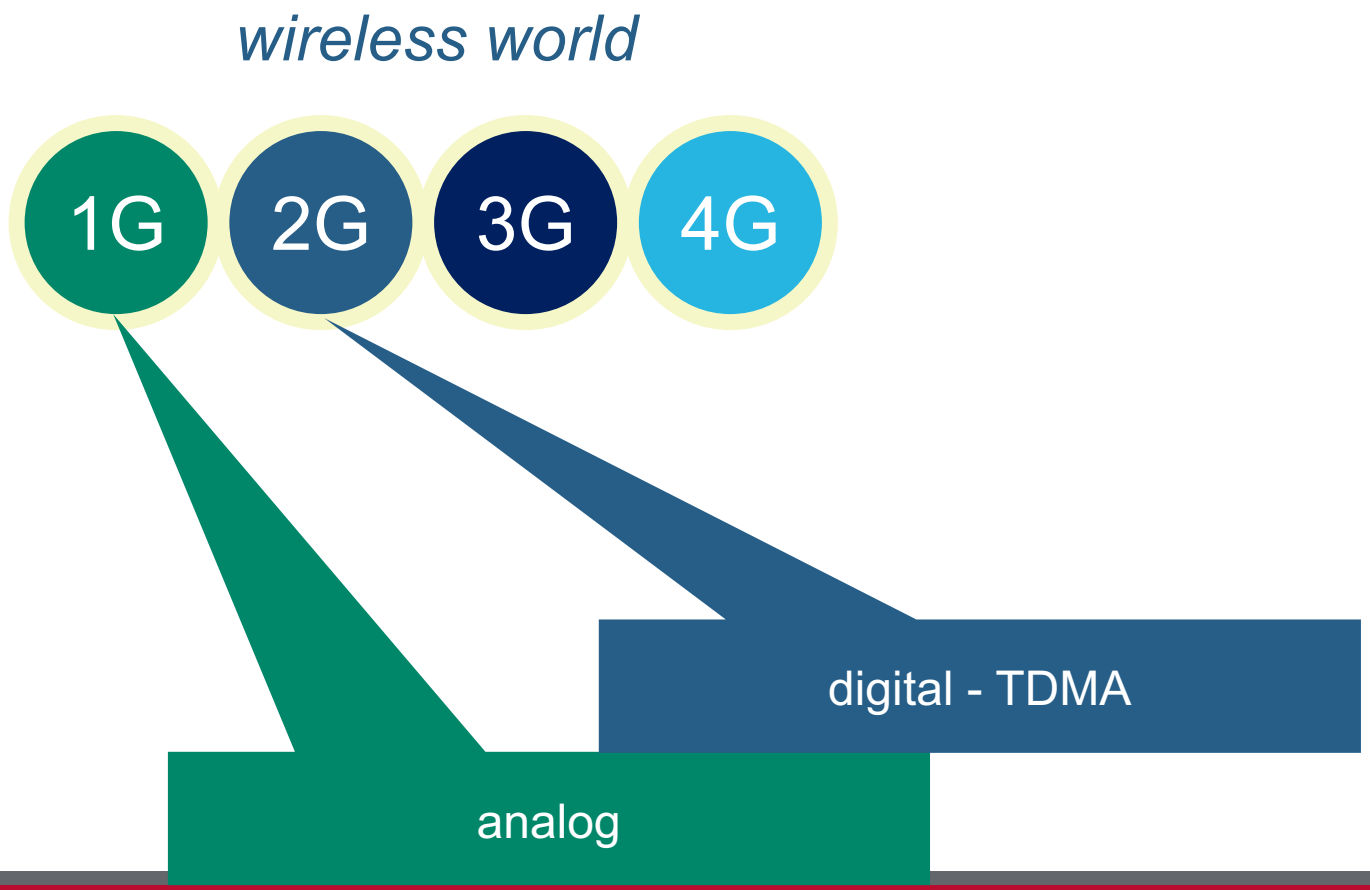

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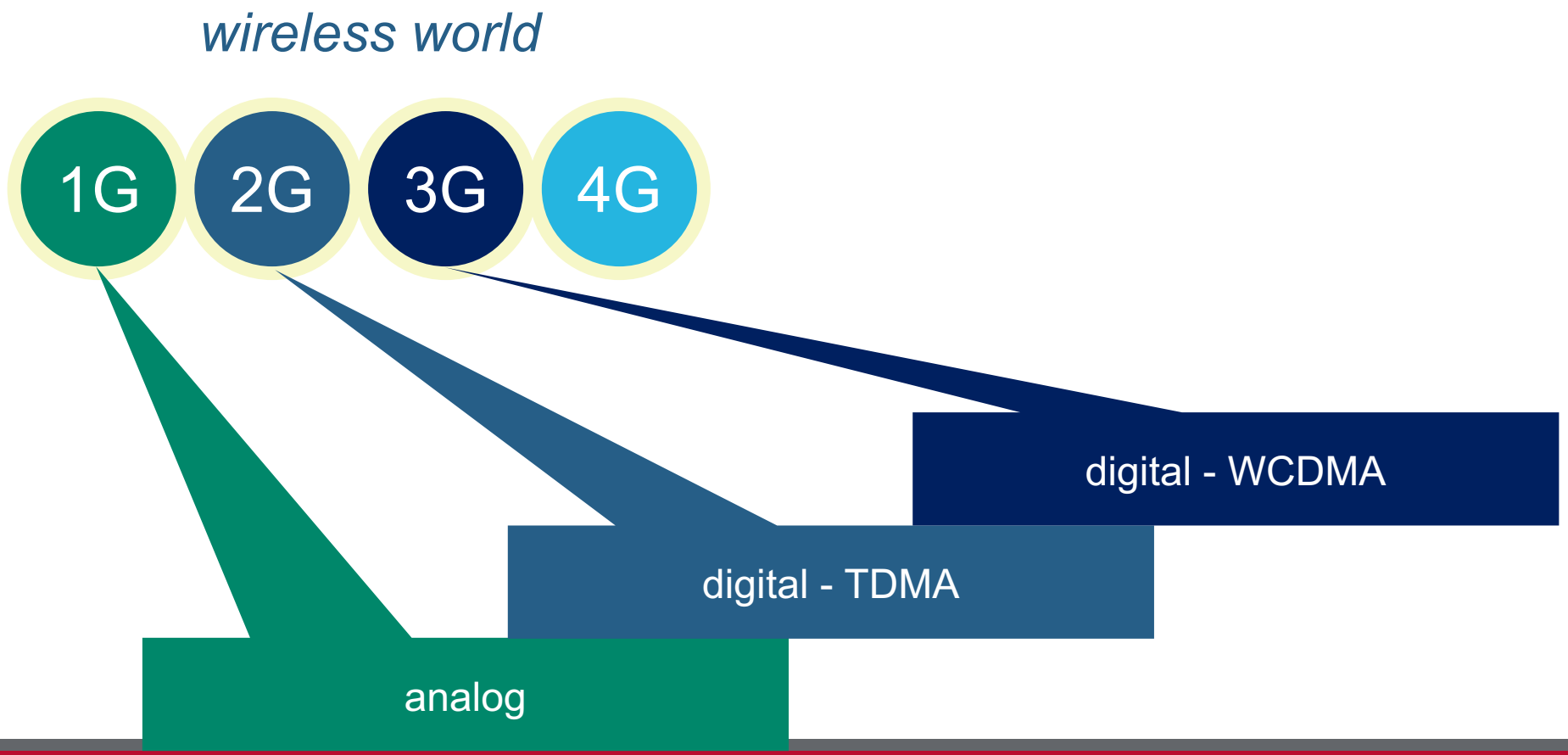

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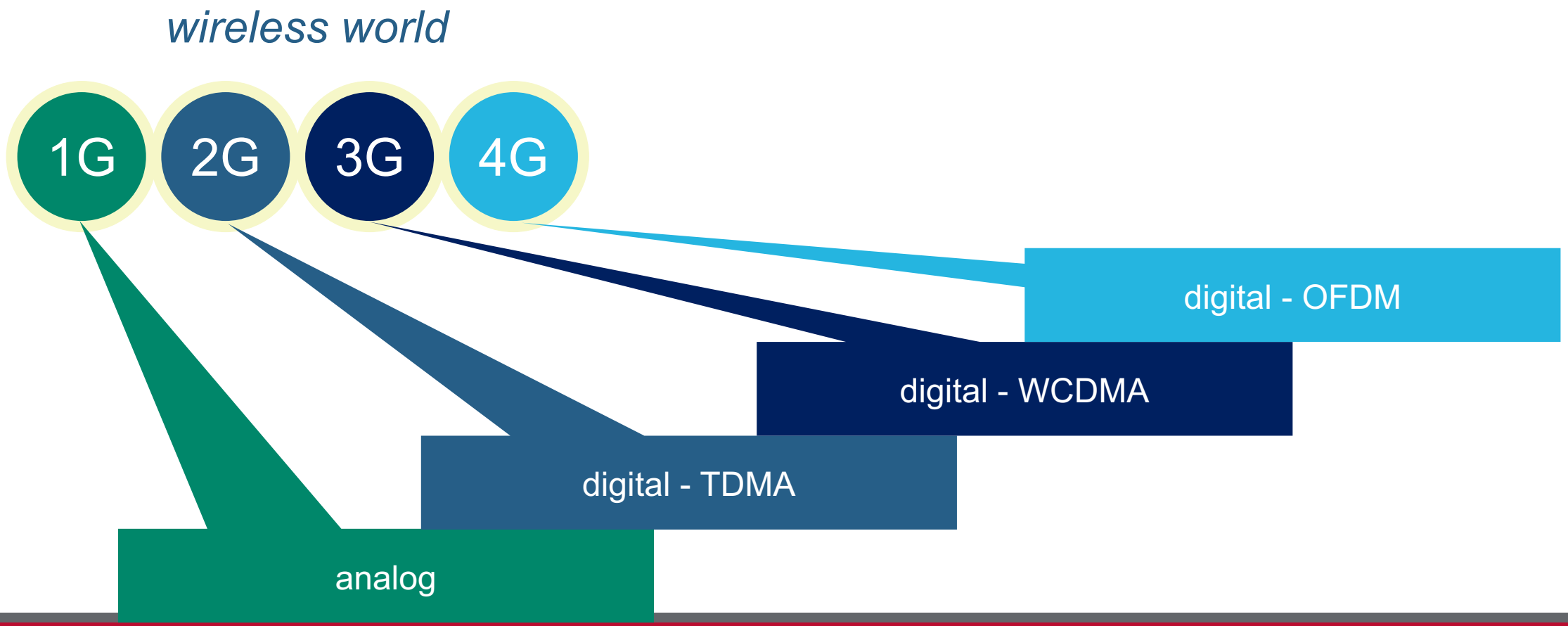


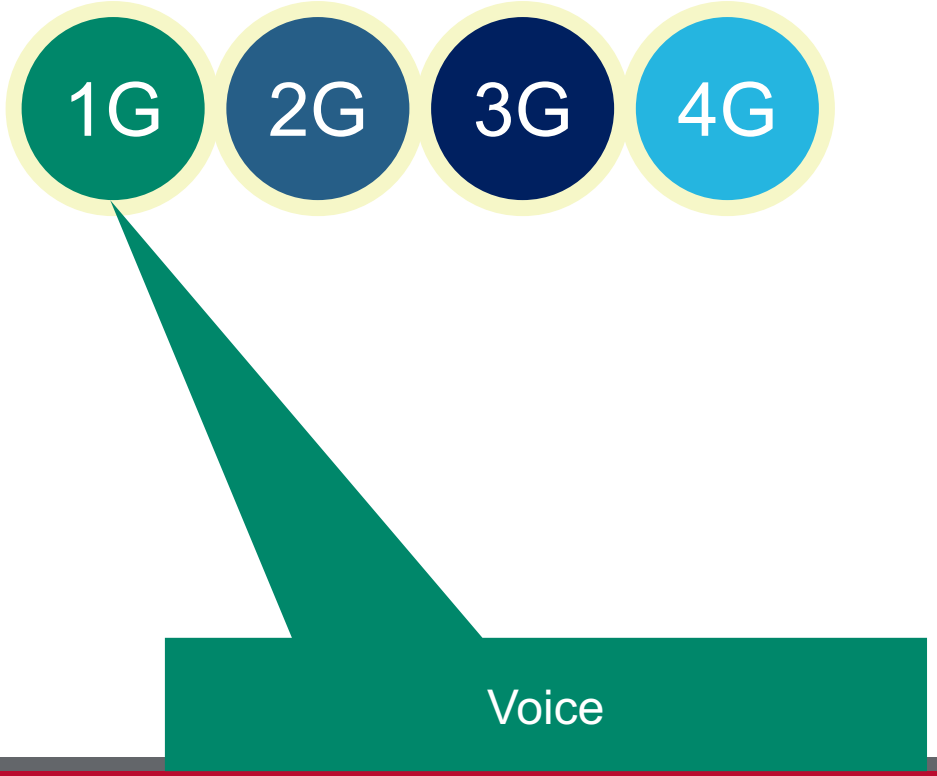
5G (r)evolution

wireless world

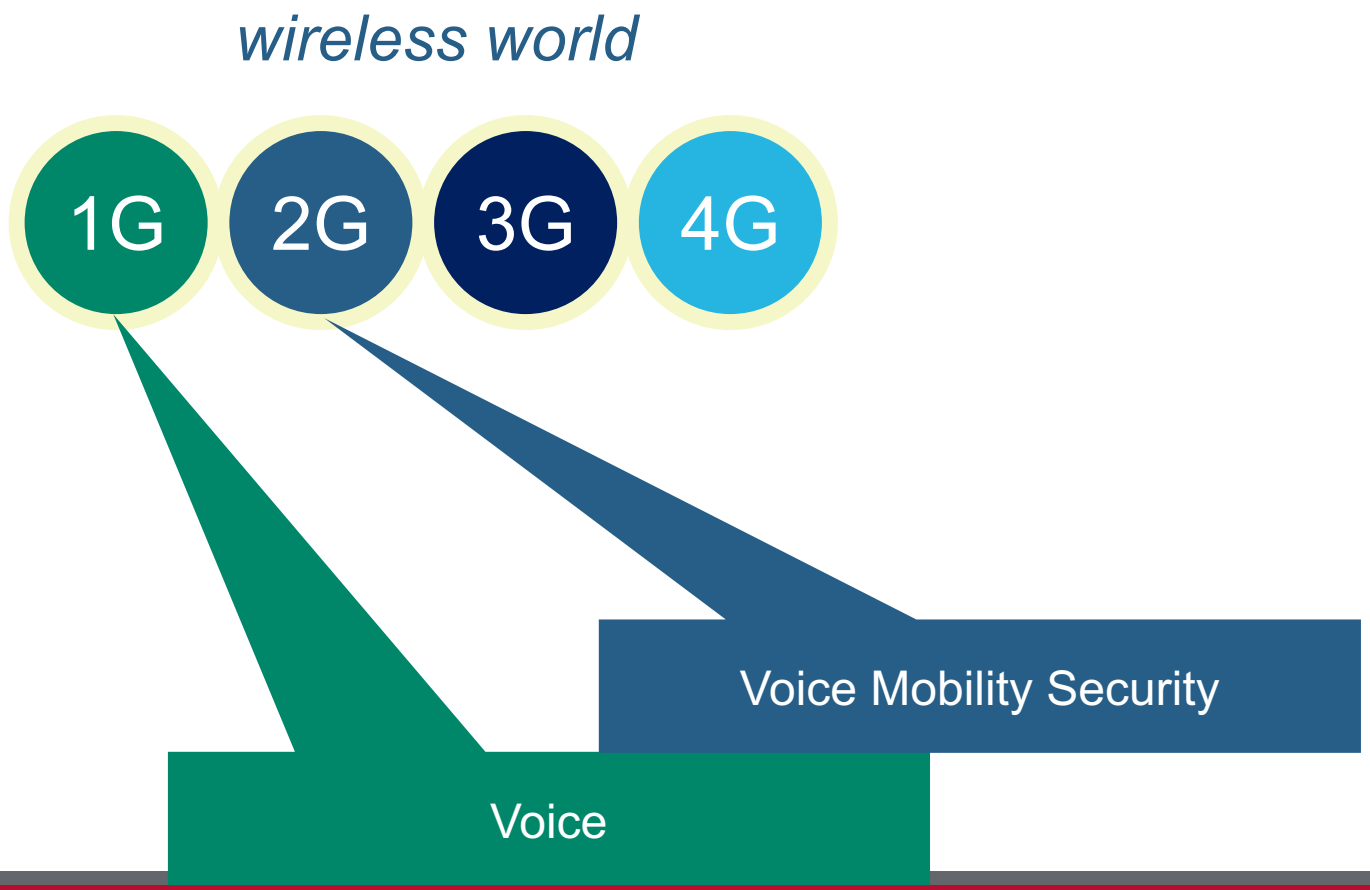
1G 2G 3G 4G

5G (r)evolution

wireless world



5G (r)evolution



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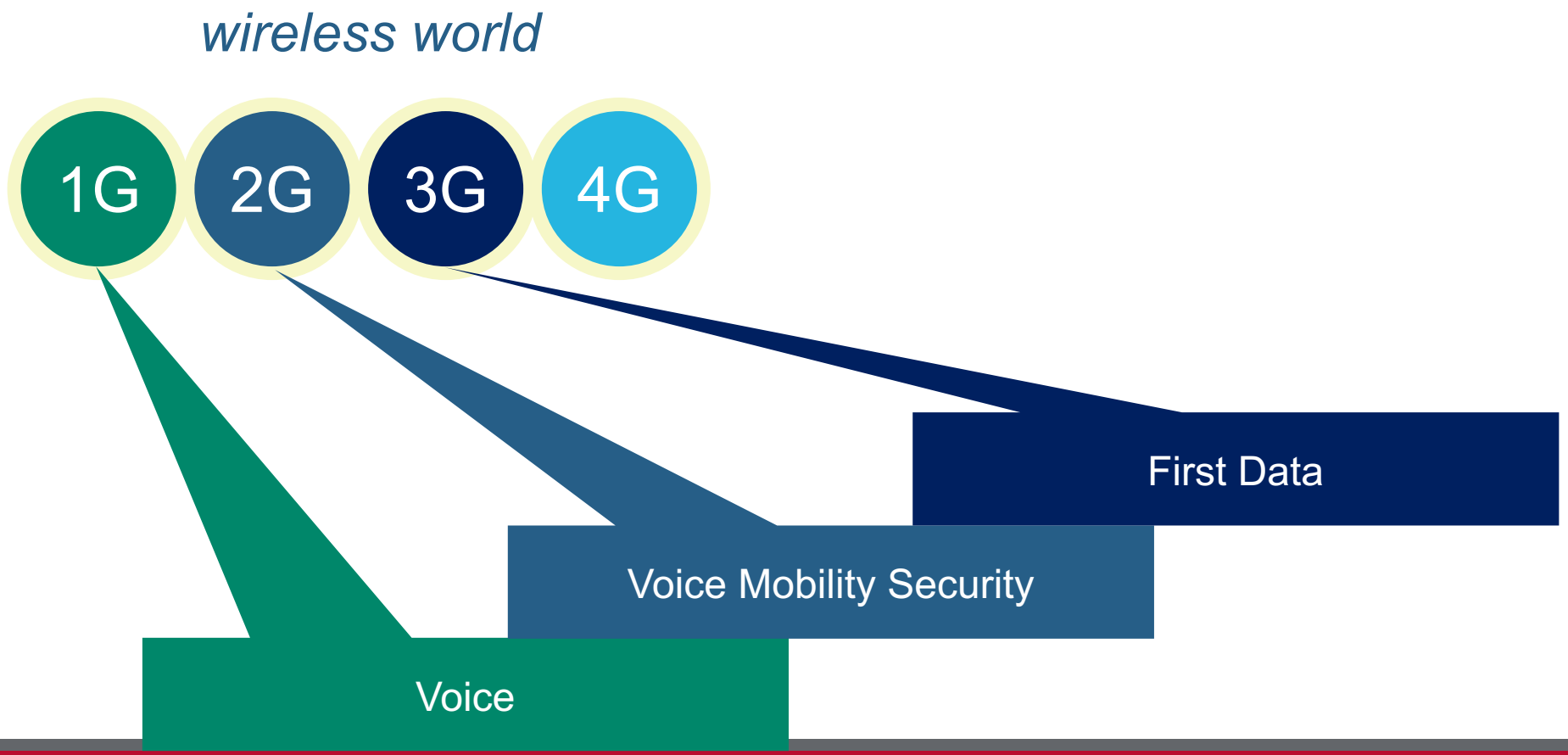

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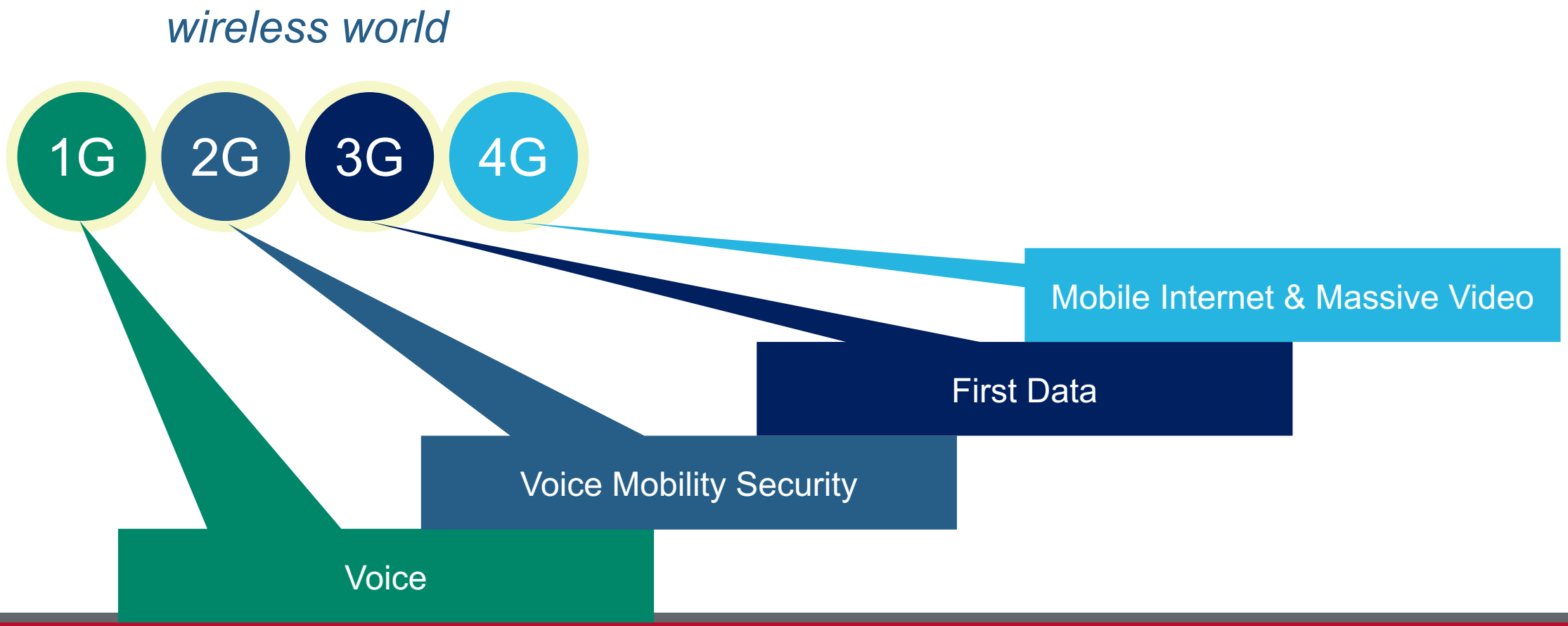
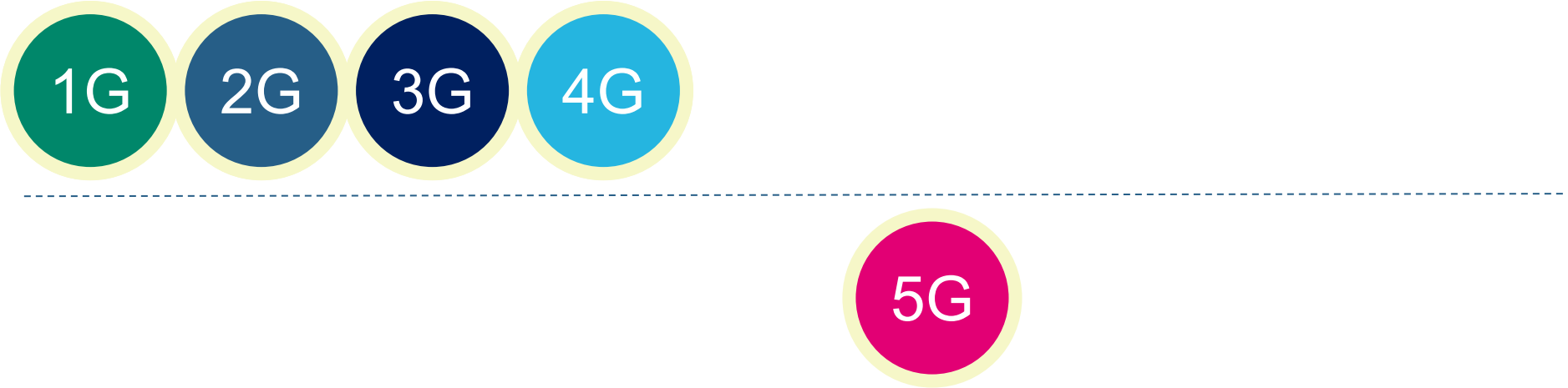
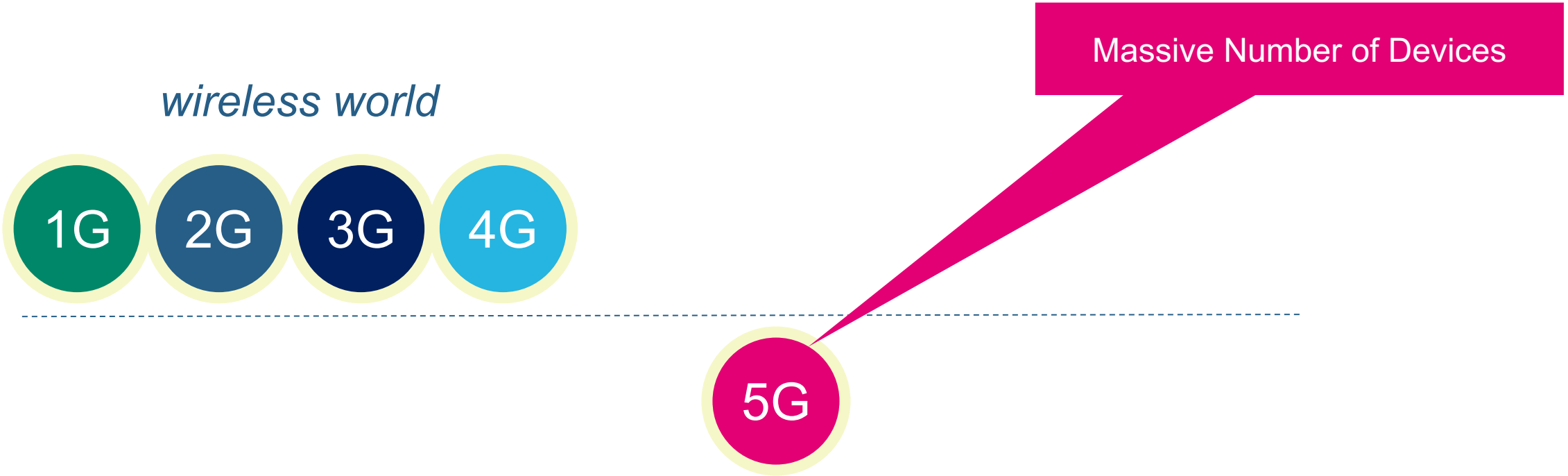


5G (r)evolution

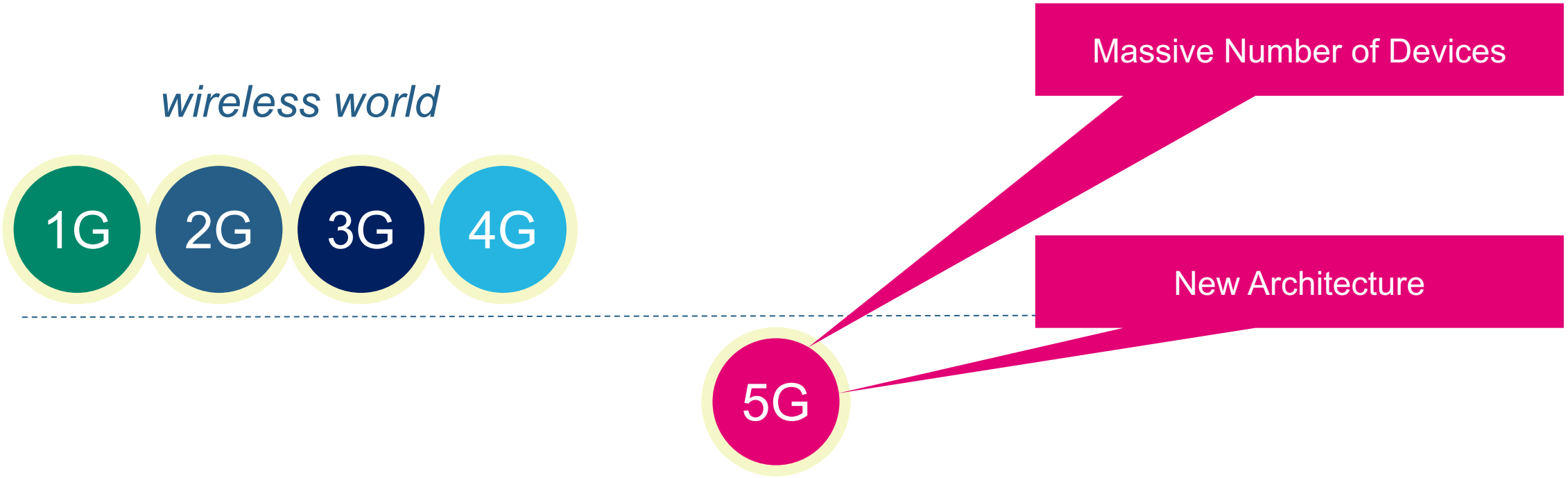
wireless world



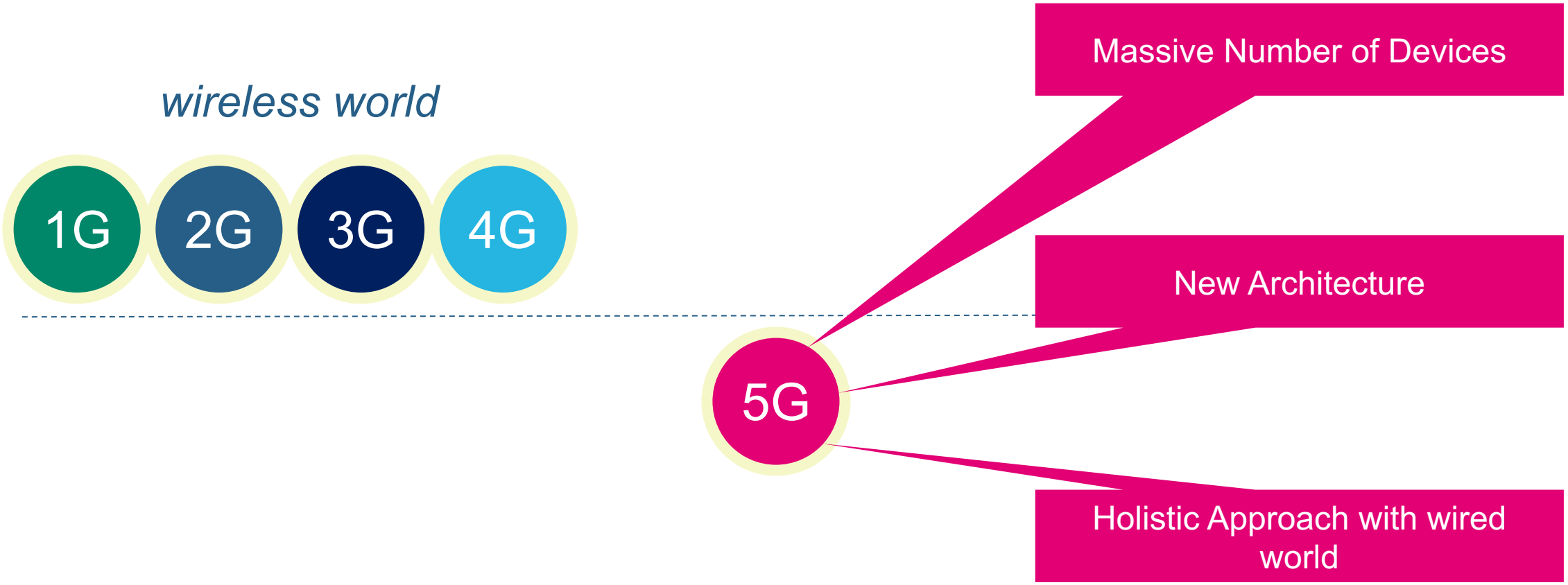
5G (r)evolution



5G (r)evolution



5G (r)evolution



5G (r)evolution

wireless world

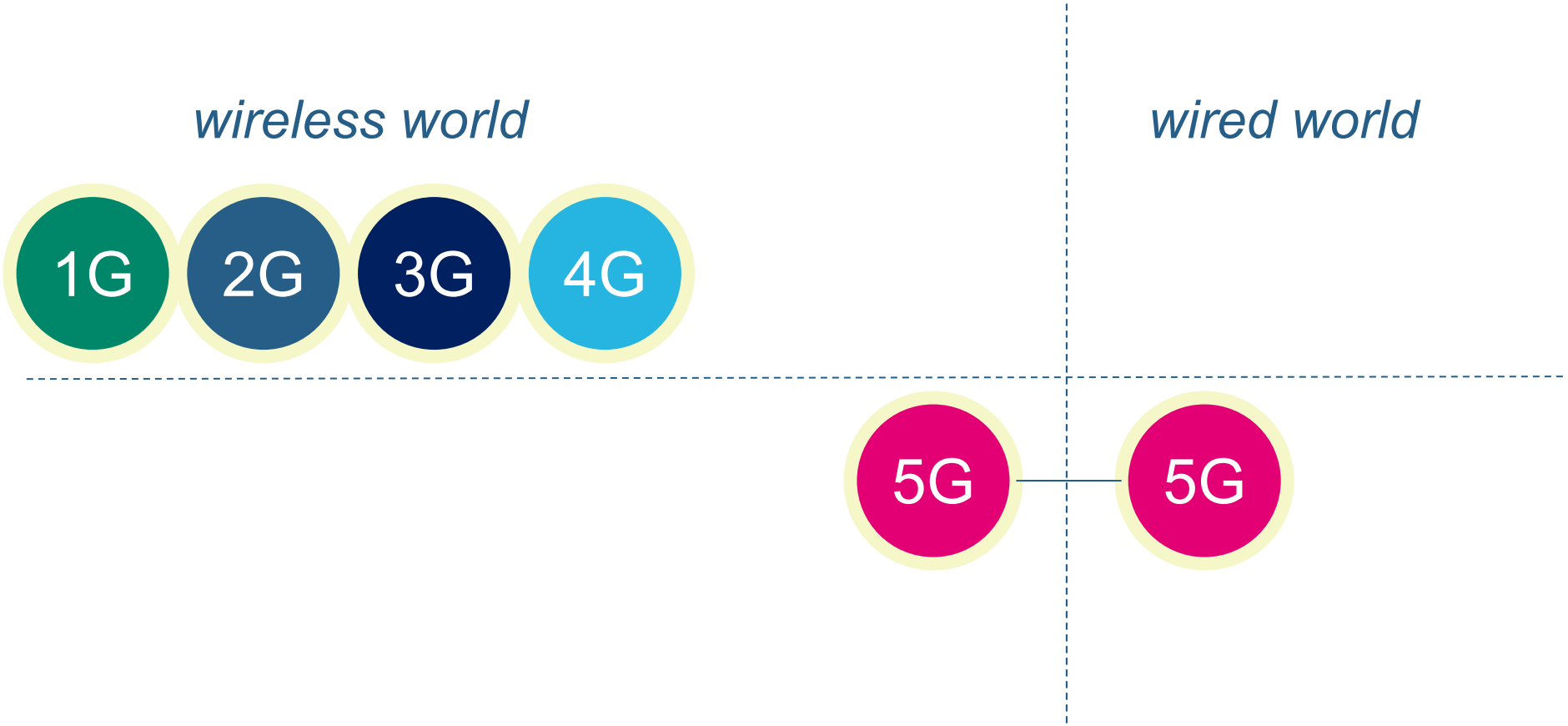
1G 2G 3G 4G

communication for consumers

5G

communication for things/control

5G (r)evolution



5G (r)evolution

wireless world

1G 2G 3G 4G

wired world

5G 5G

5G

IETF®

5G (r)evolution

wireless world

1G 2G 3G 4G 10y

wired world

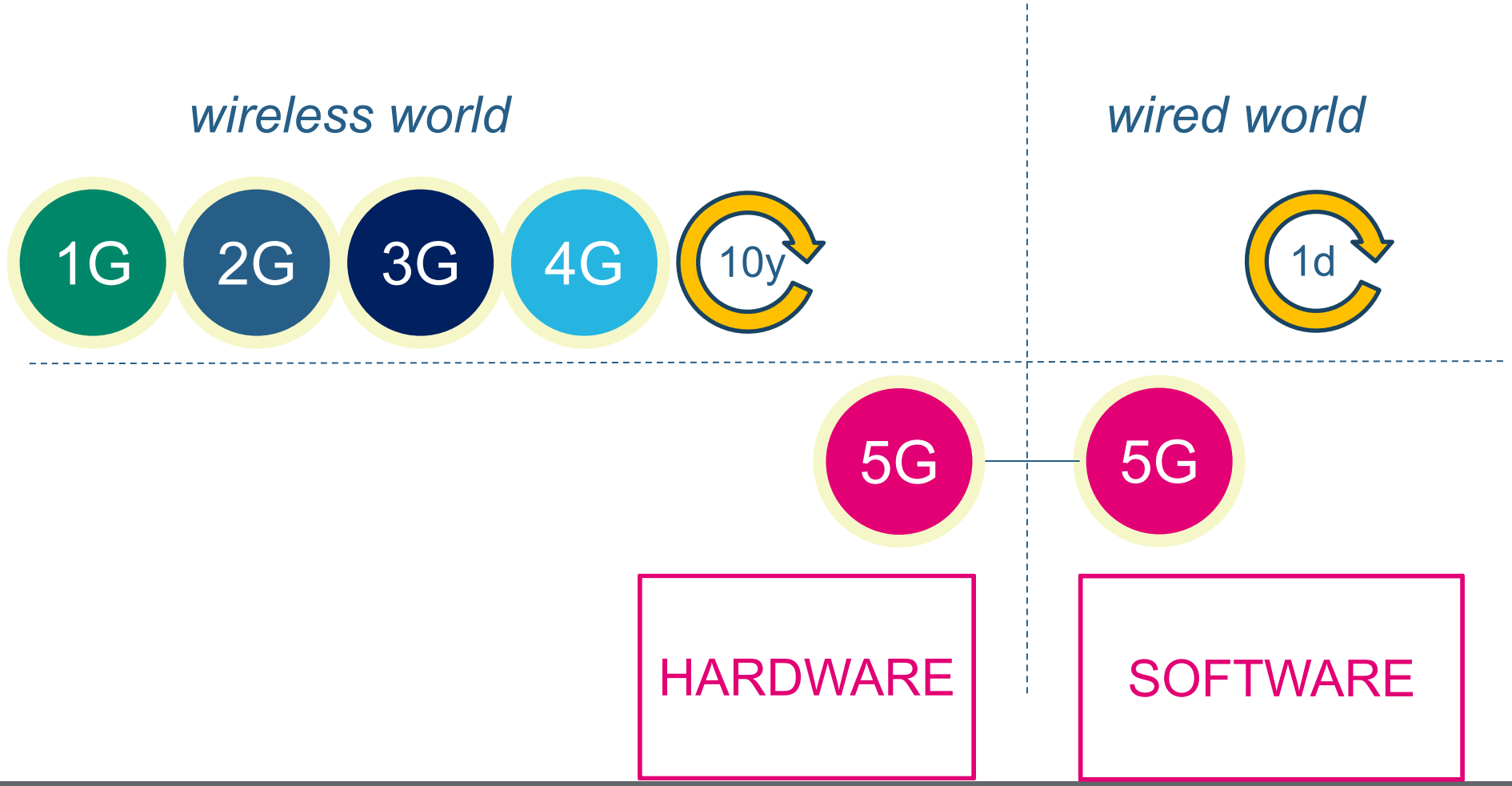
1d

5G 5G

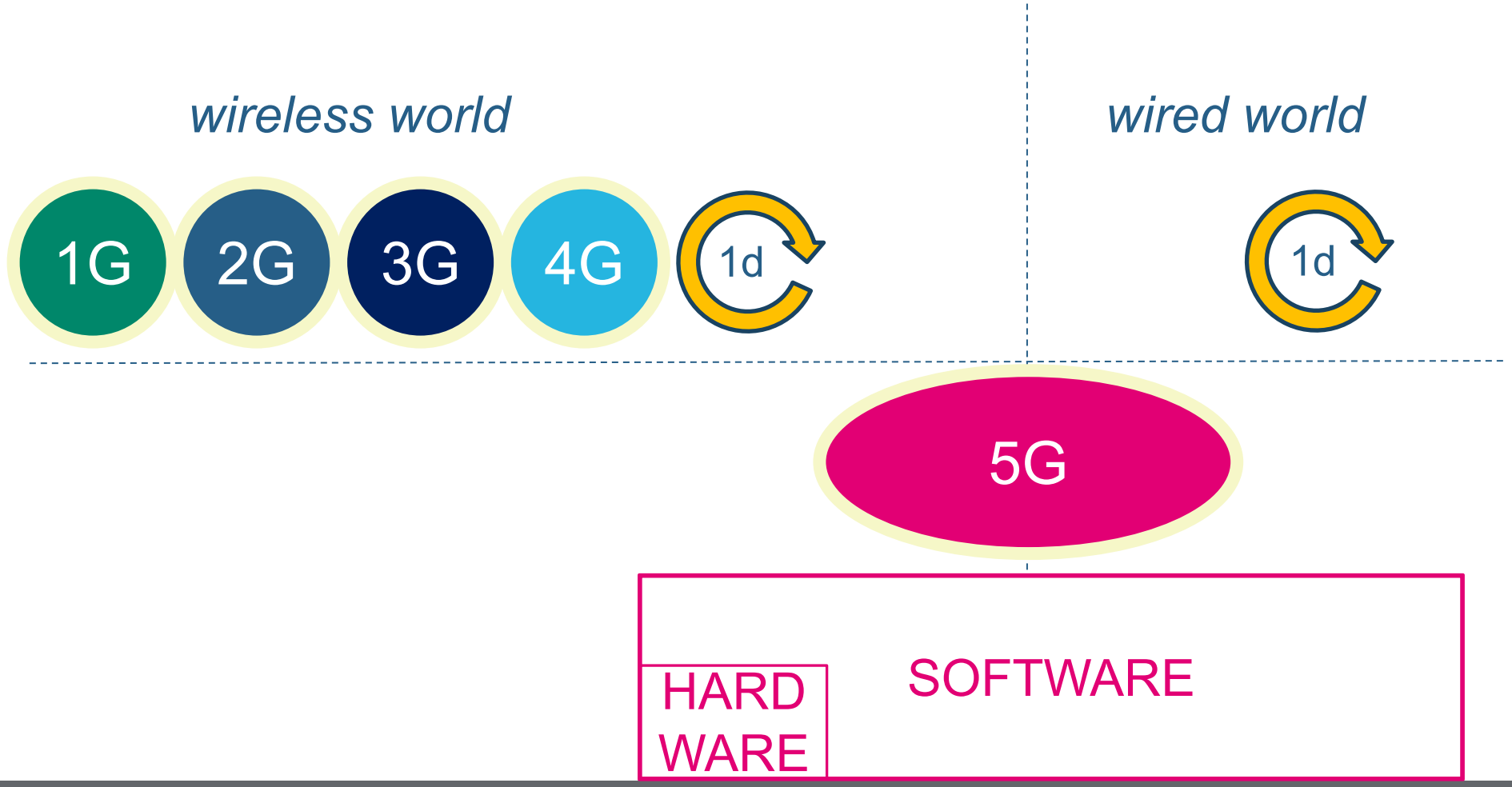
5G

IETF®

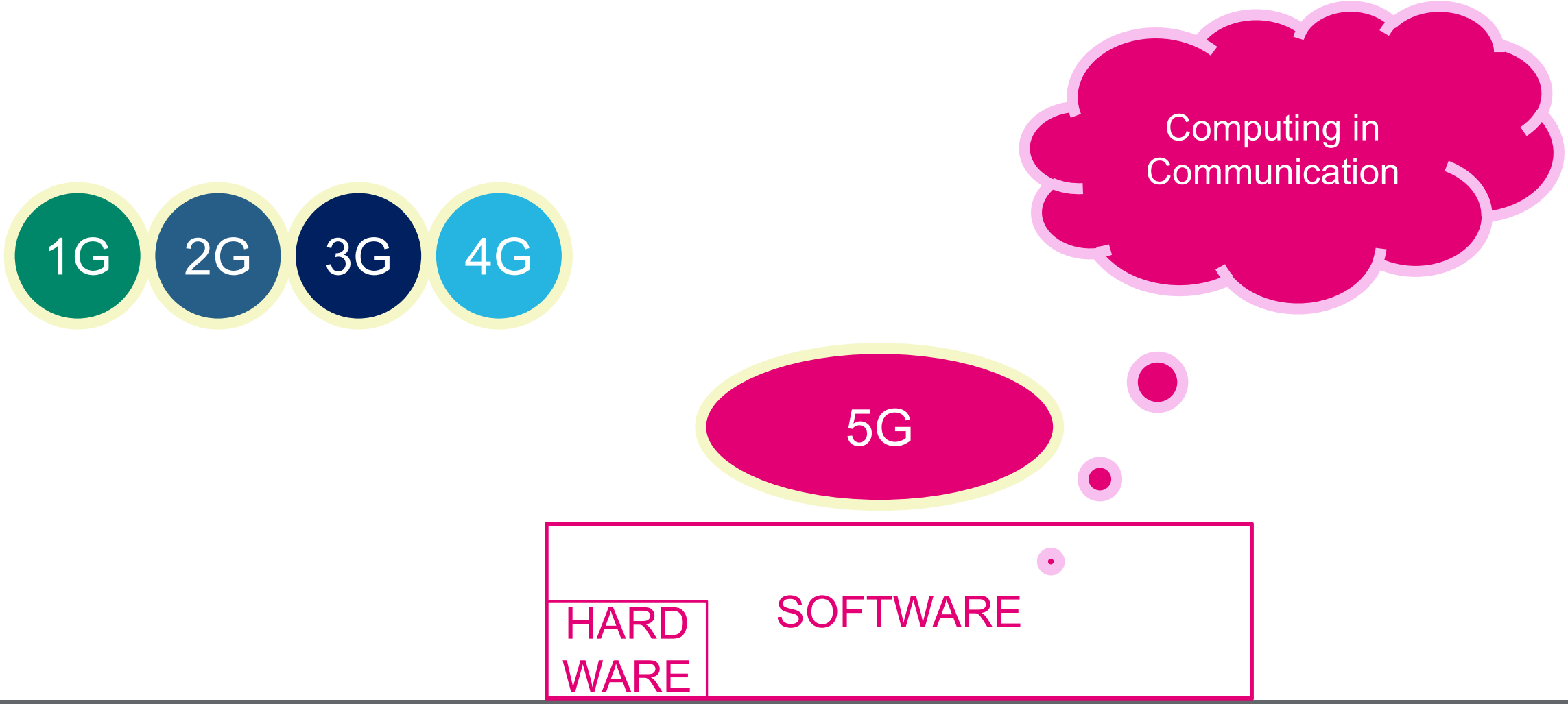
5G (r)evolution



5G (r)evolution



5G (r)evolution



5G (r)evolution

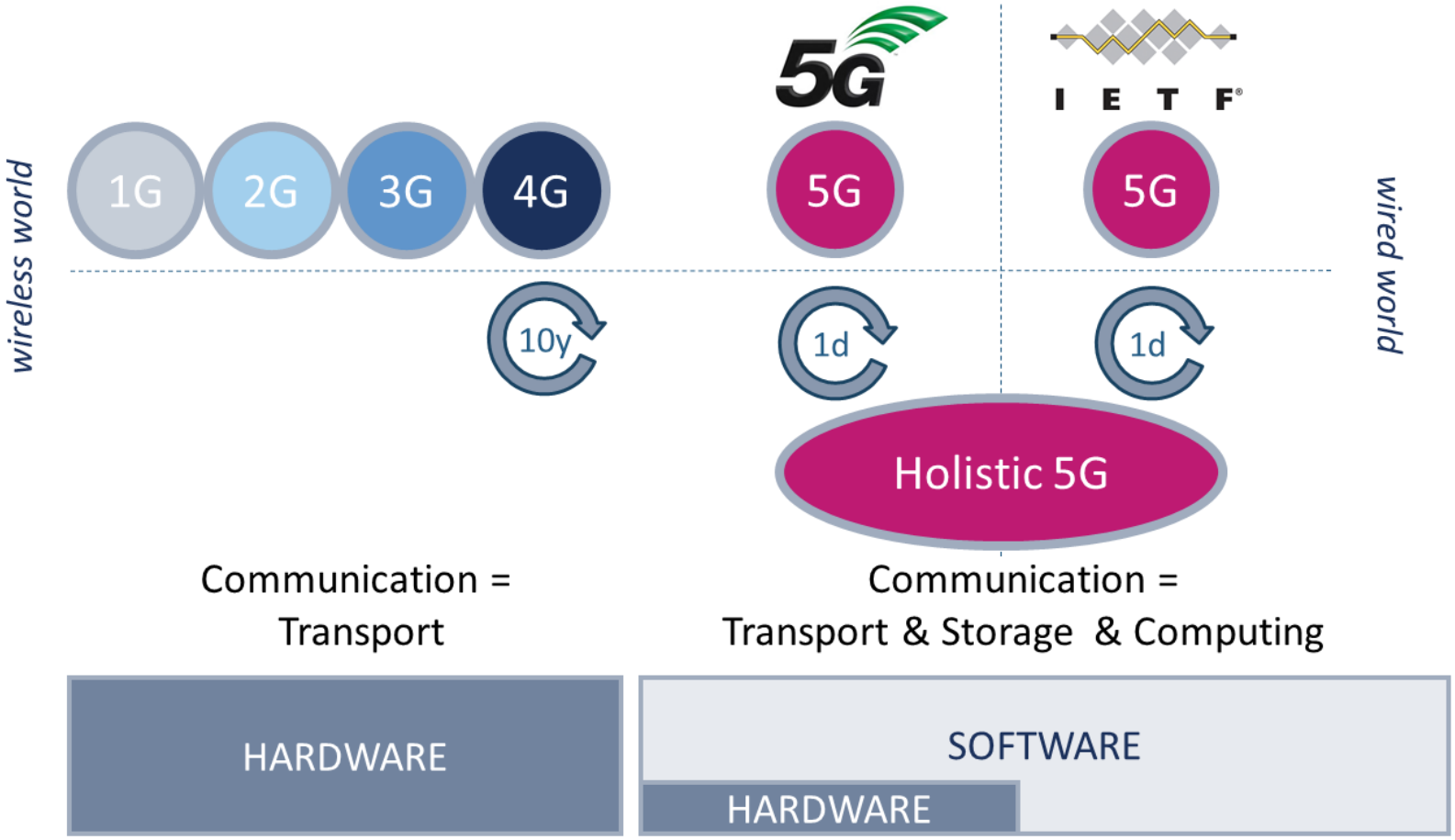
1G 2G 3G 4G

Communication = Transport

5G

Communication = Transport
Storage
Computing

The evolution of cellular communication systems



What defines 5G?

Massive Number of Devices

7

Billion Devices

2014

Massive Number of Devices

7

Billion Devices

2014

500

Billion Devices

2022

Massive Number of Devices

7

Billion Devices

2014

Throughput

500

Billion Devices

2022

Massive Number of Devices

7

Billion Devices

2014

Throughput

but there is more ....

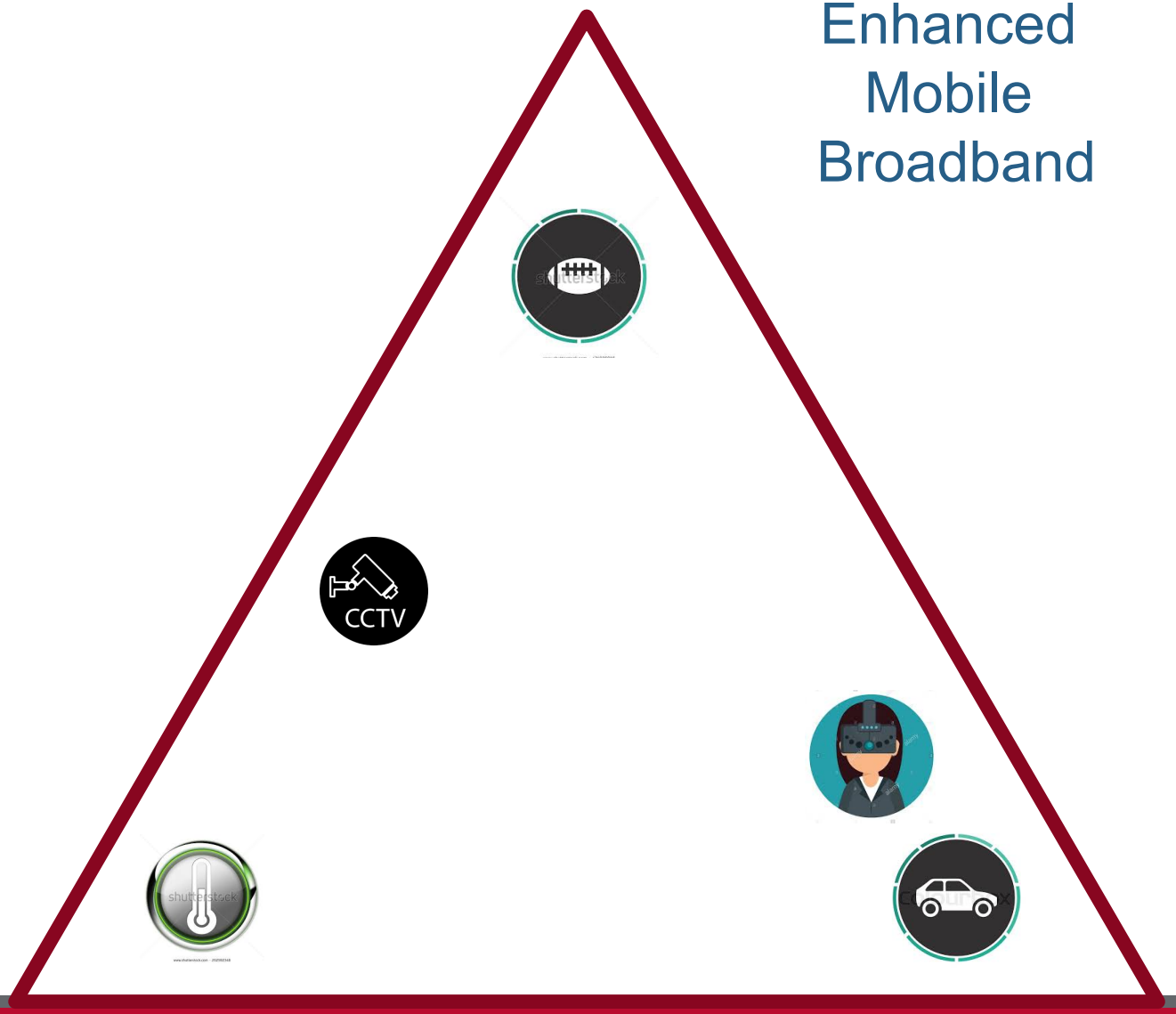
500

Billion Devices

2022

What defines 5G?
IMT 2020

General 5G Definition ITU-R IMT 2020

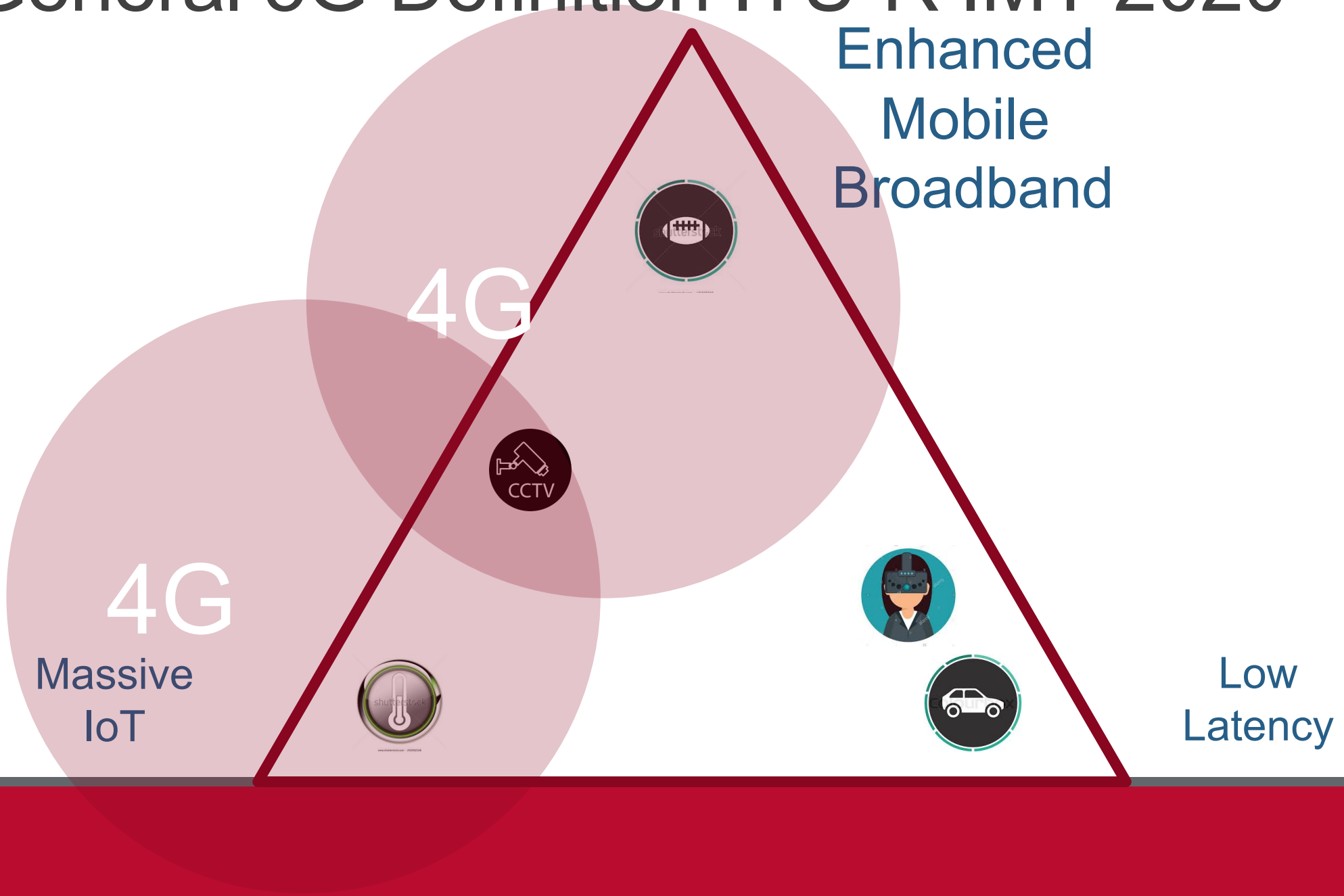


Enhanced Mobile Broadband

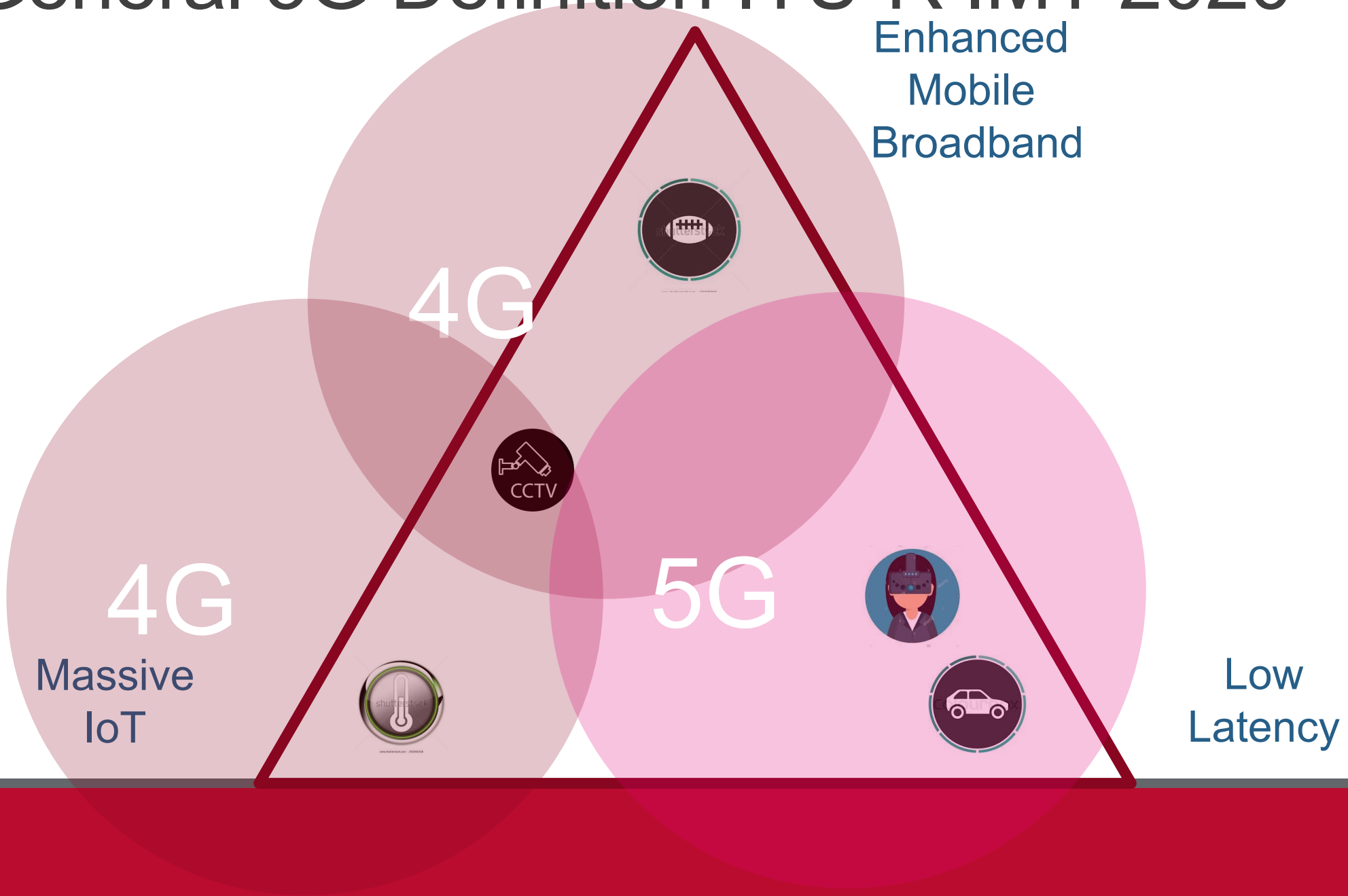
Massive IoT

Low Latency

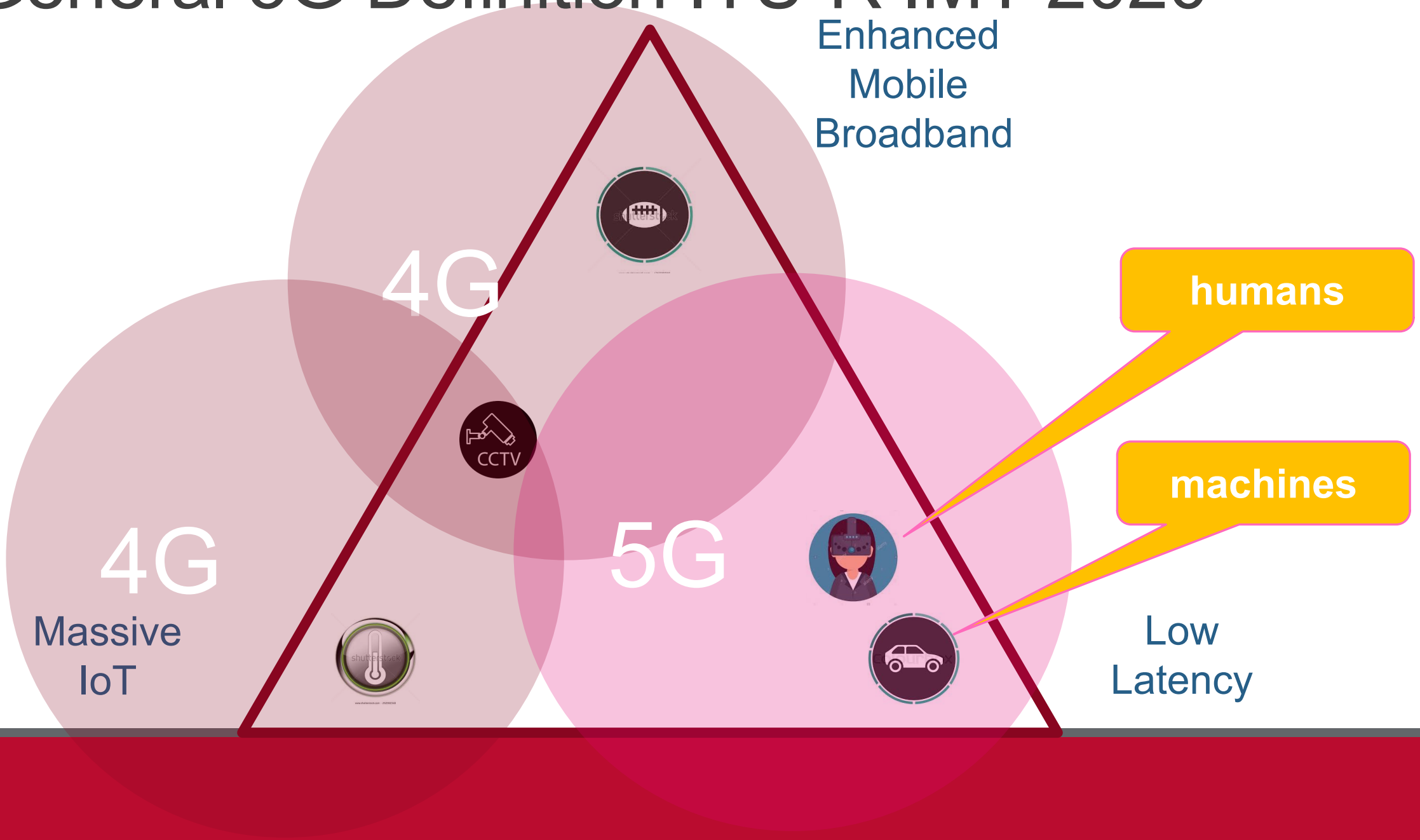
General 5G Definition ITU-R IMT 2020



General 5G Definition ITU-R IMT 2020



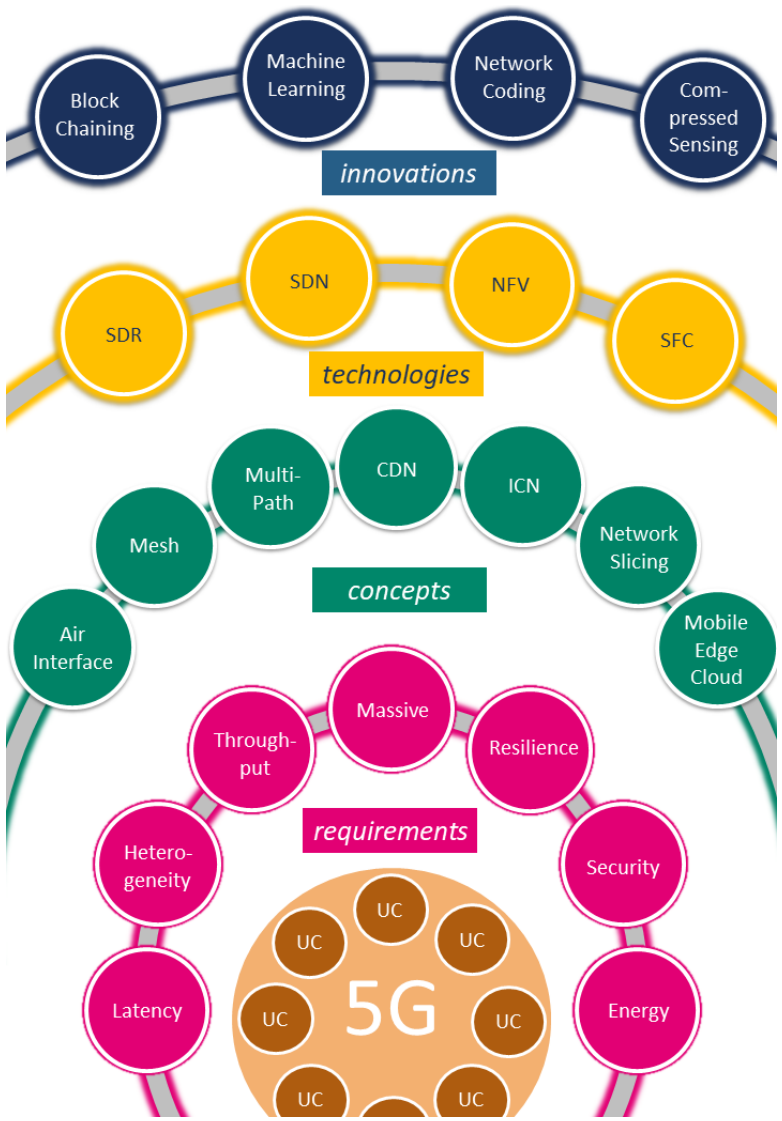
General 5G Definition ITU-R IMT 2020



What defines 5G?
The 5G atom

The 5G Atom

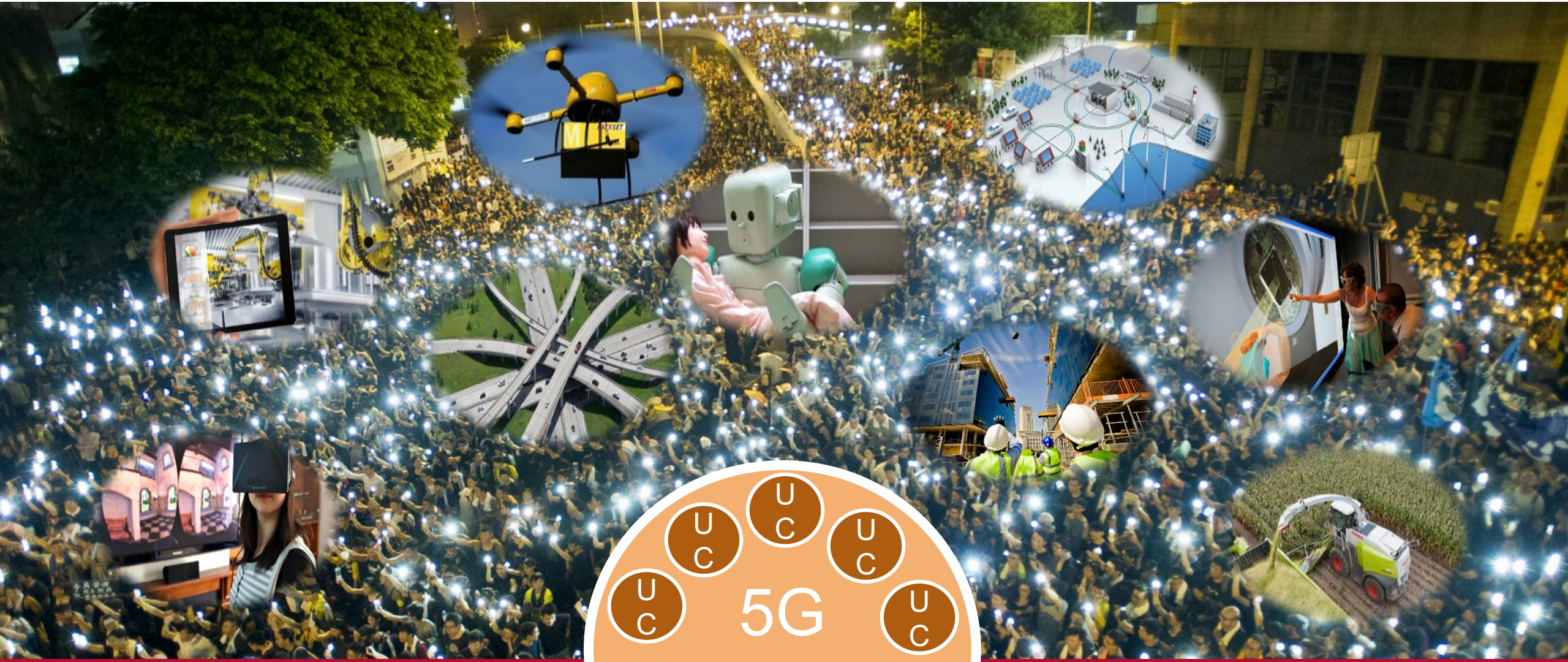
- Our definition of 5G by atom
  - Core → Use Cases
  - Electrons → Elements



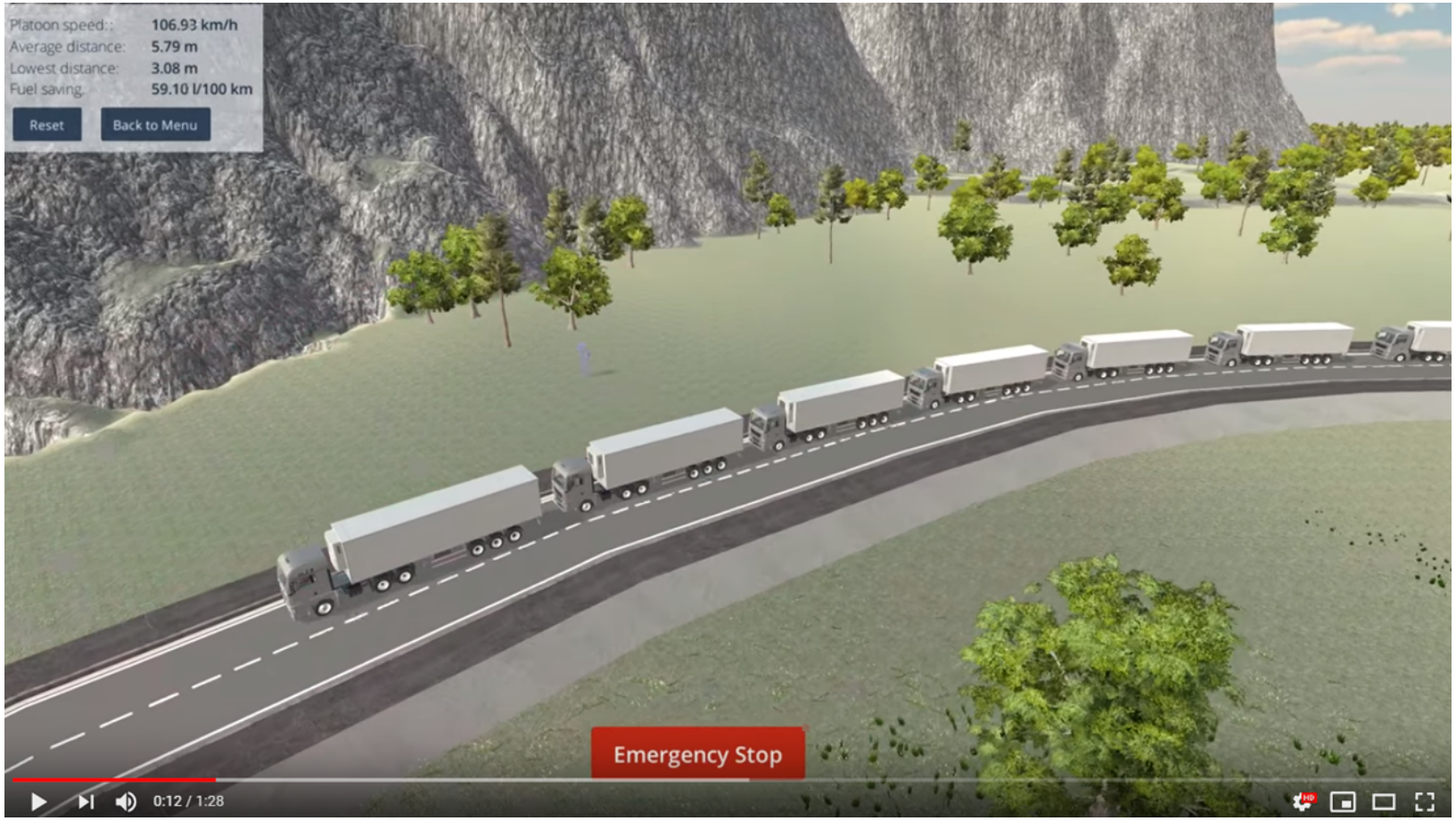
5G Use Cases

5G atom definition

5G atom definition

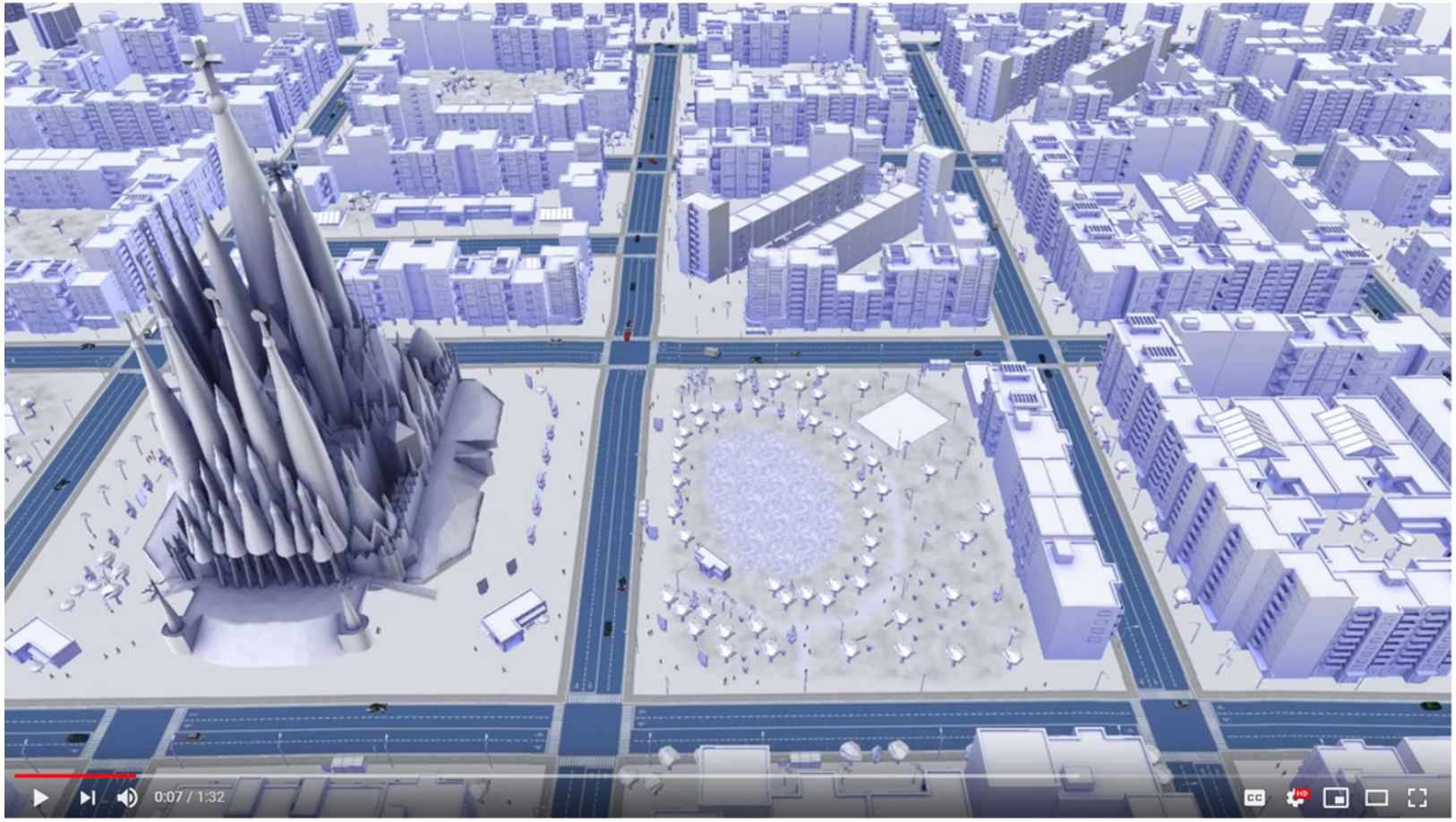


The 5G Atom use cases:
Connected autonomous cars platooning example



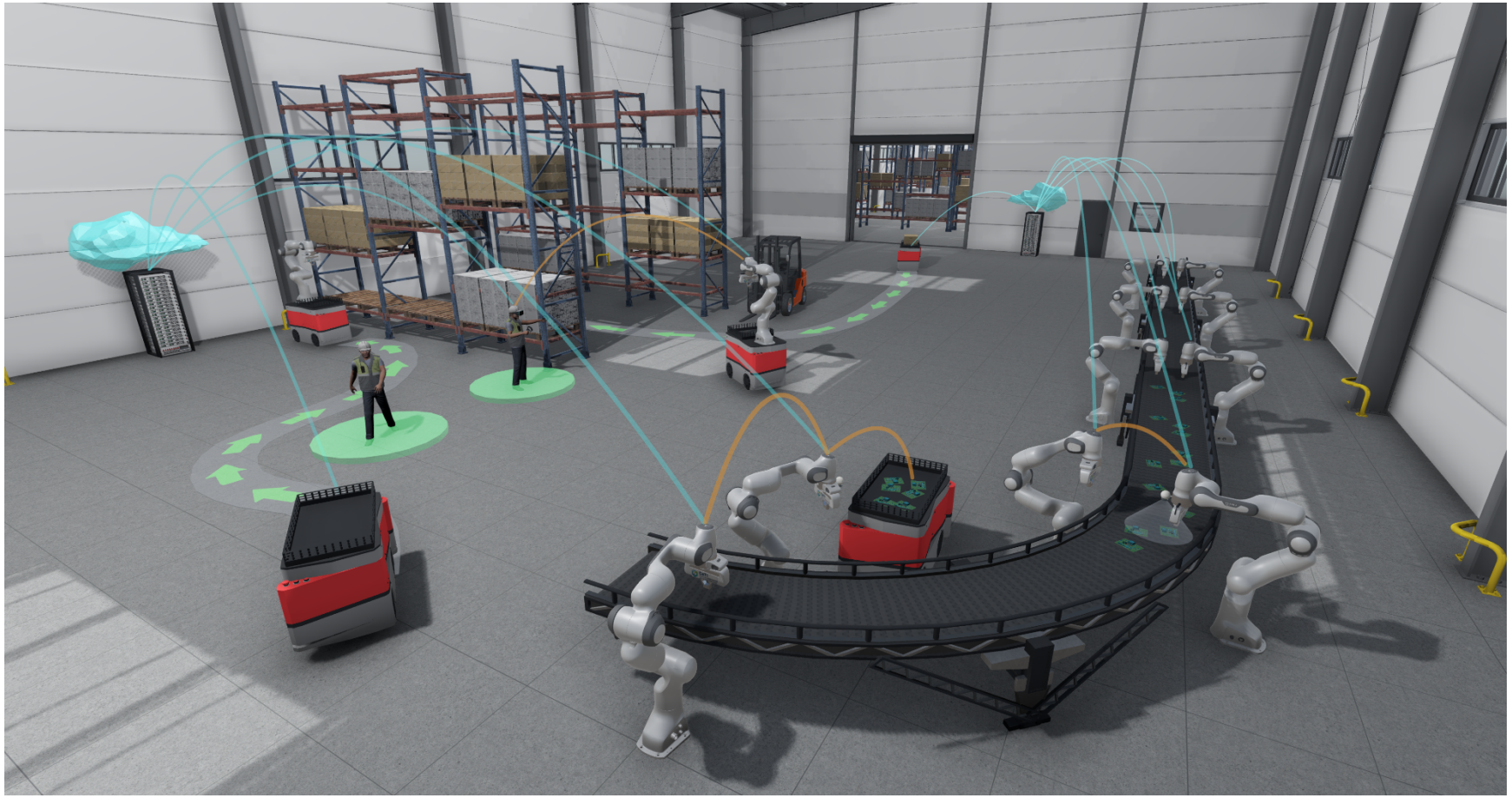
https://www.youtube.com/watch?v=3R3t_hVsj9c

The 5G Atom use cases:
Connected autonomous cars Barcelona example

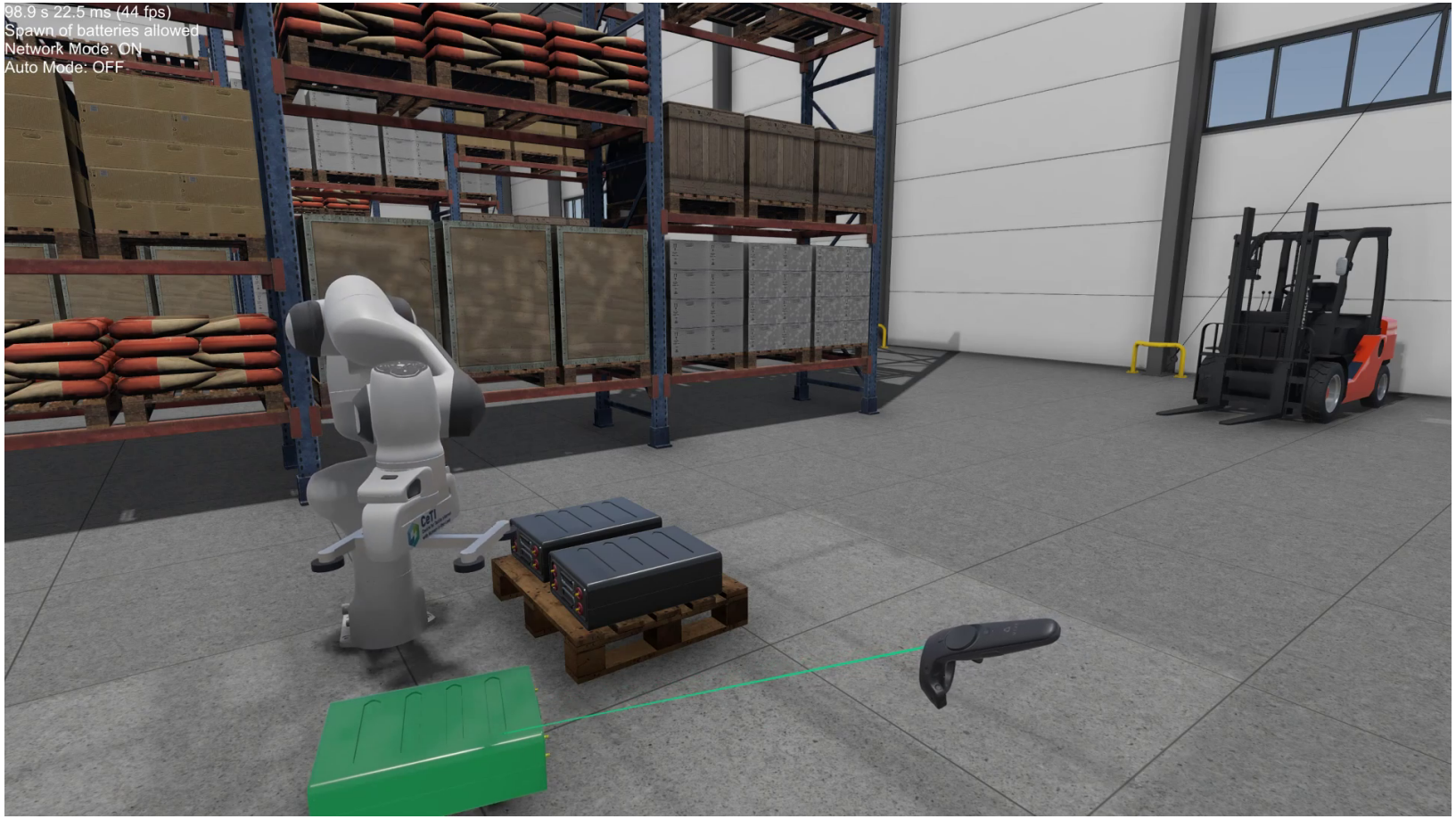


https://www.youtube.com/watch?v=C8fy3IIVlB0&t=27s

The 5G Atom use cases:
Example network architecture in Industry 4.0

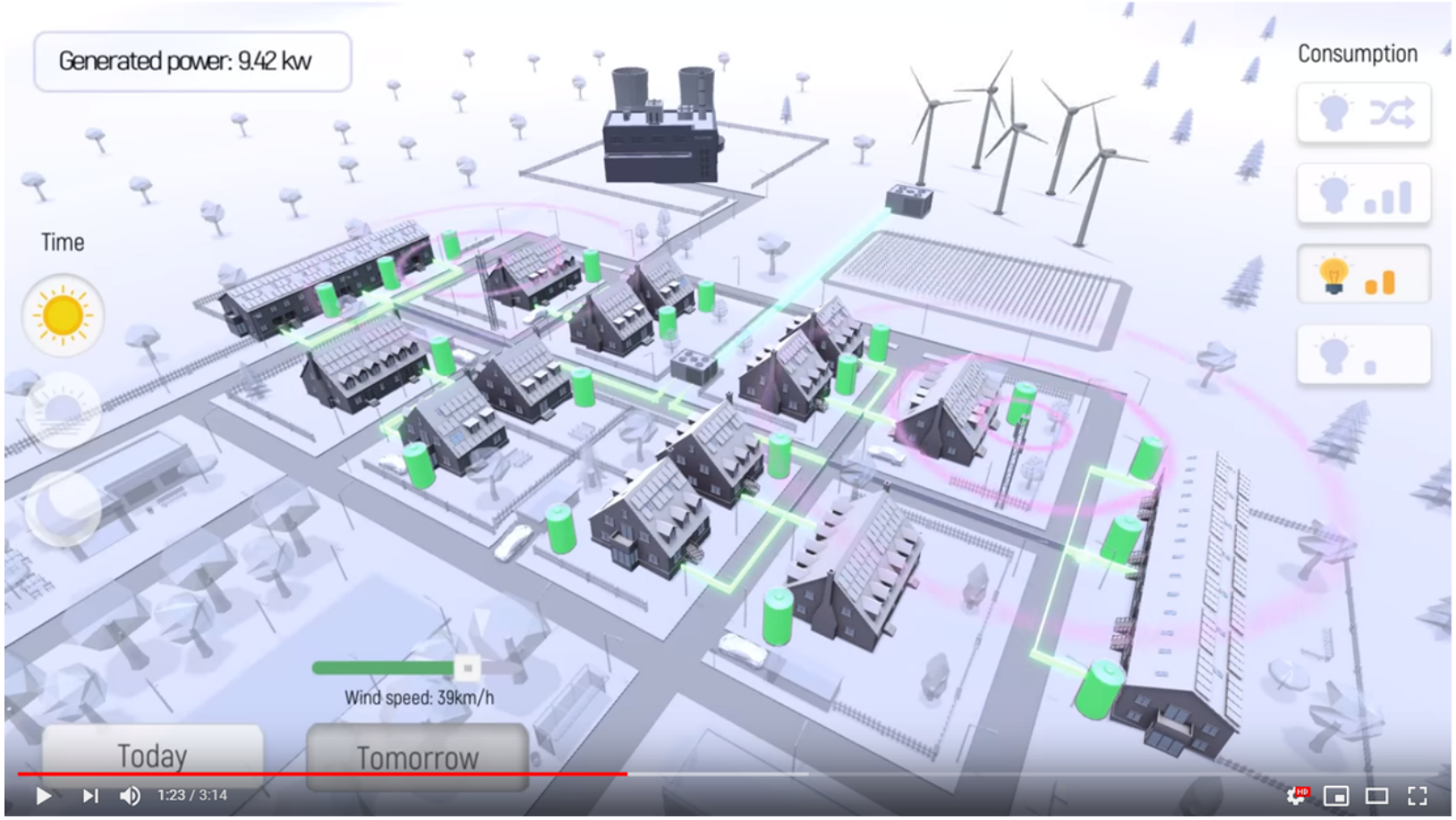


The 5G Atom use cases:
Industry 4.0 training or remote control of robots in a virtual room



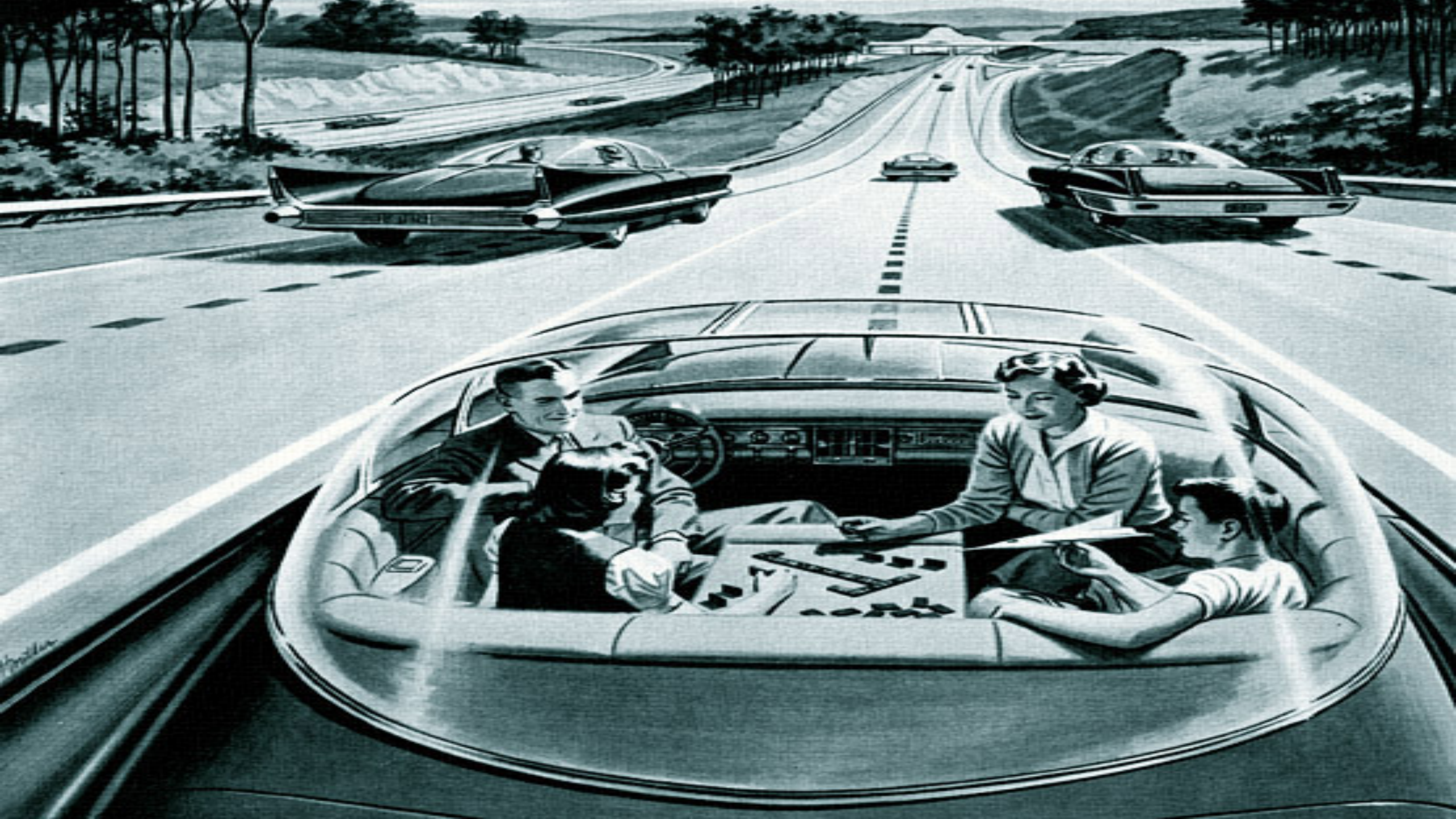
The 5G Atom use cases: Agriculture 4.0 machinery platooning with small machines

The 5G Atom use cases:
Virtual power plant model for the smart energy grid



https://www.youtube.com/watch?v=WqaZly_1LRg&t=8s

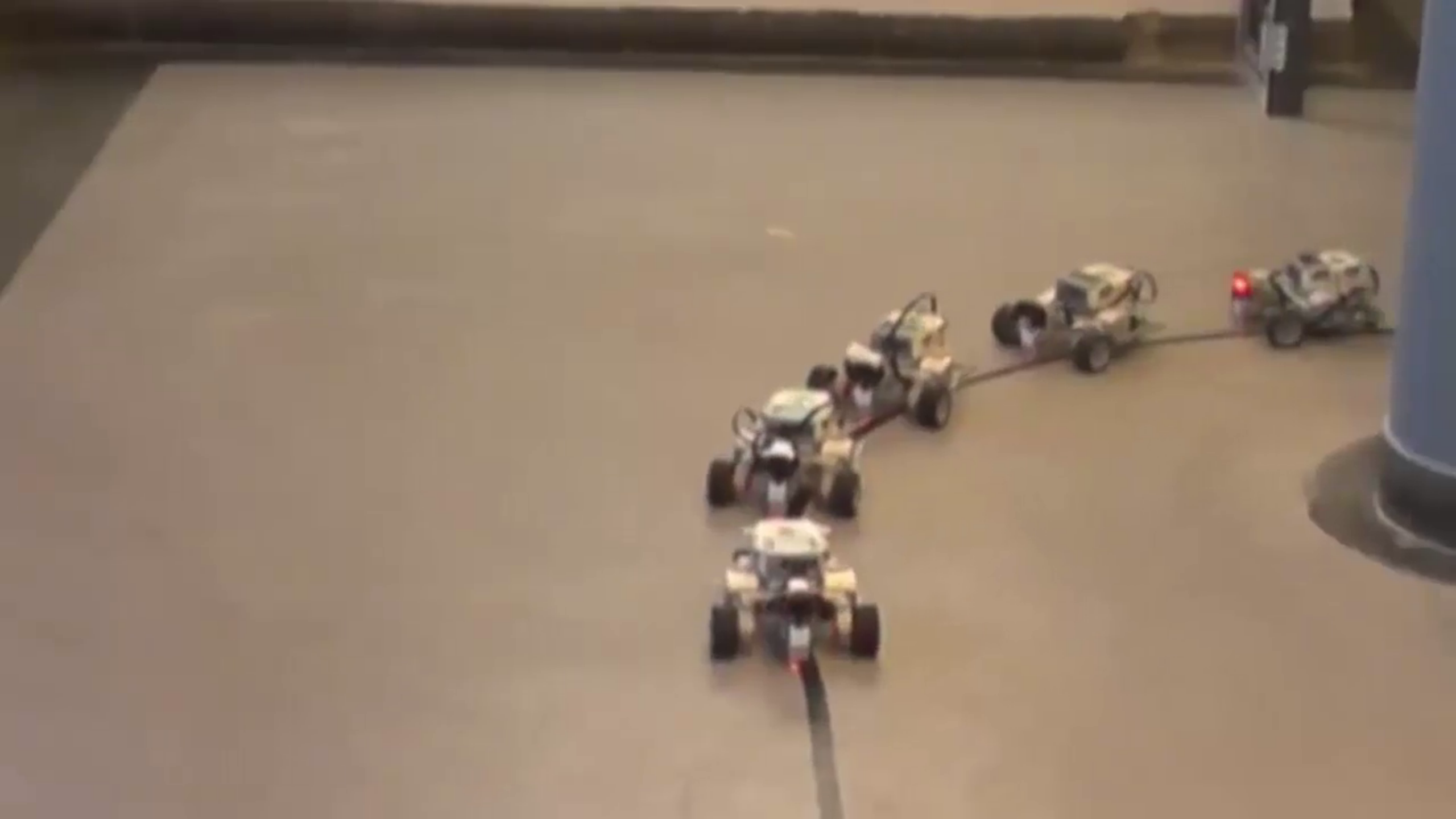
The 5G Atom use cases: Tactile Internet



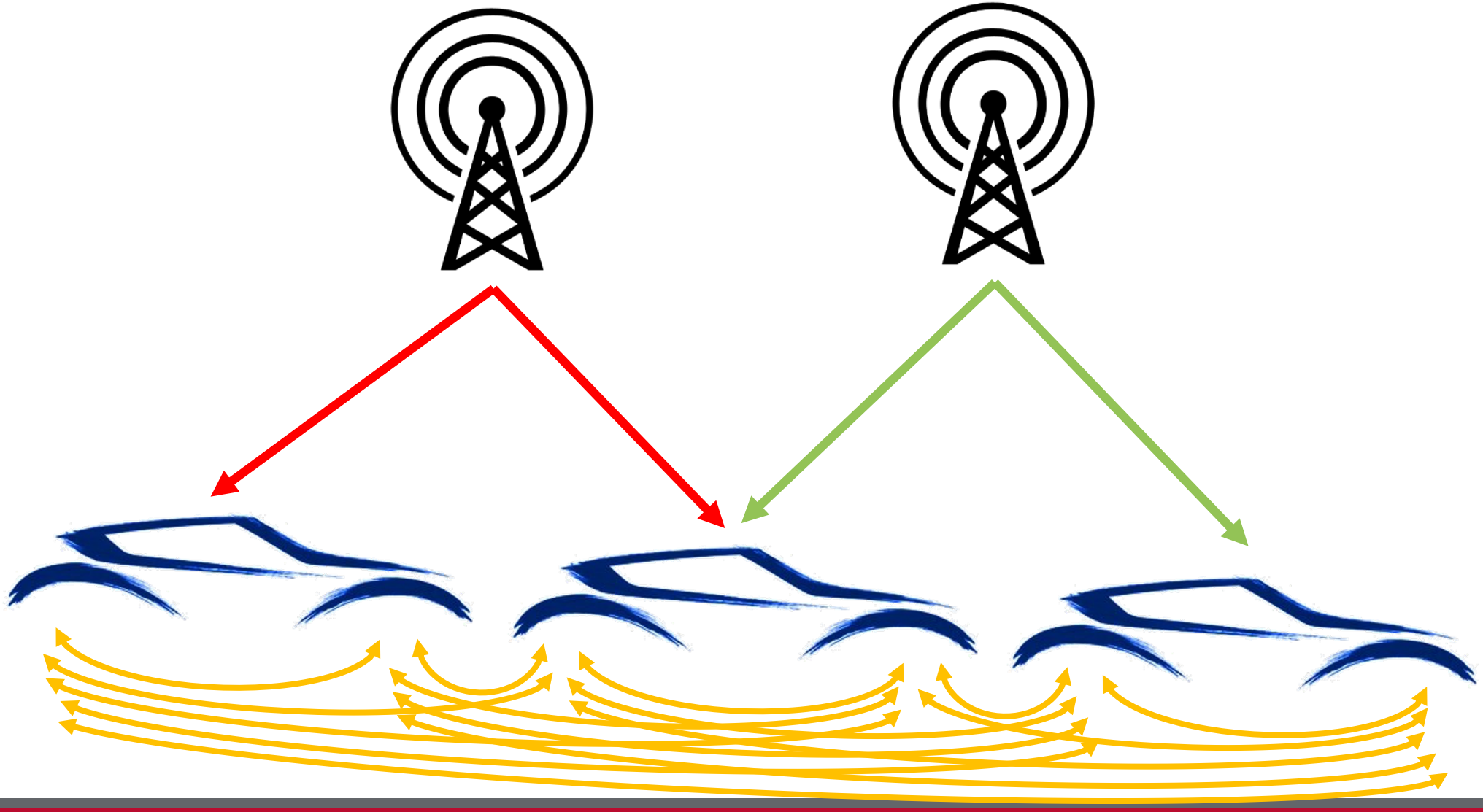
Platooning

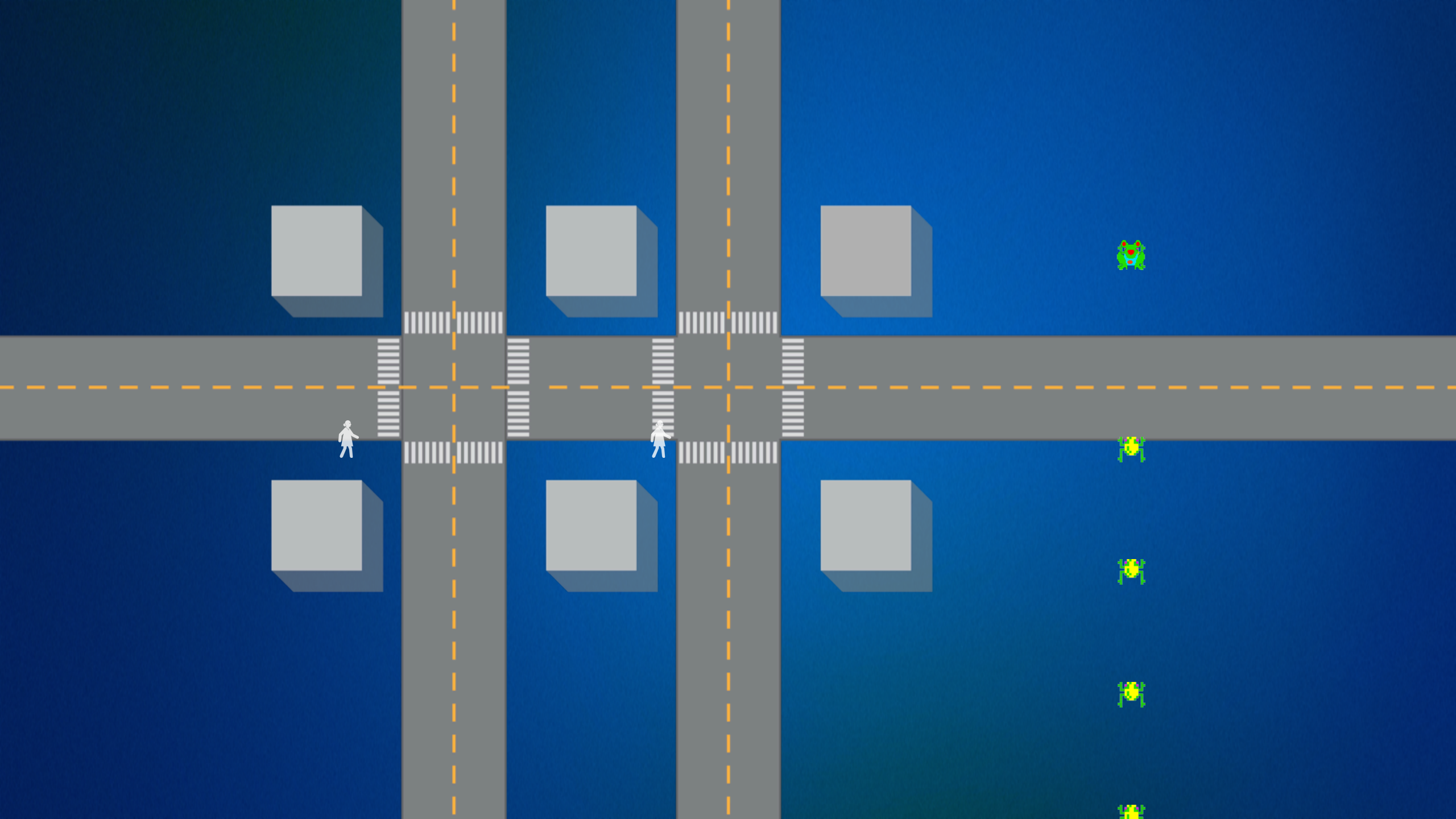
1-2 ms: ESC, ABS

Platooned ESC & ABS



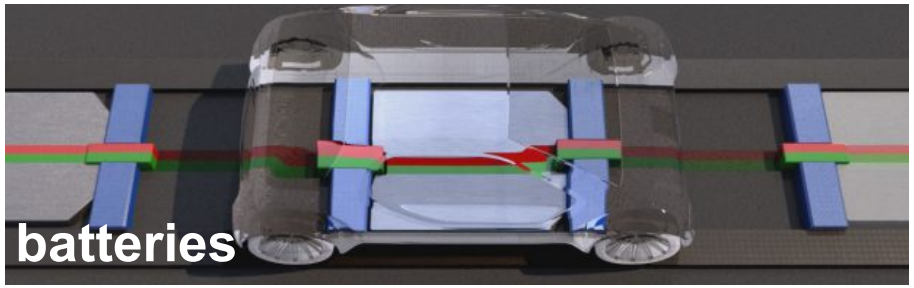
Car Communication Networks

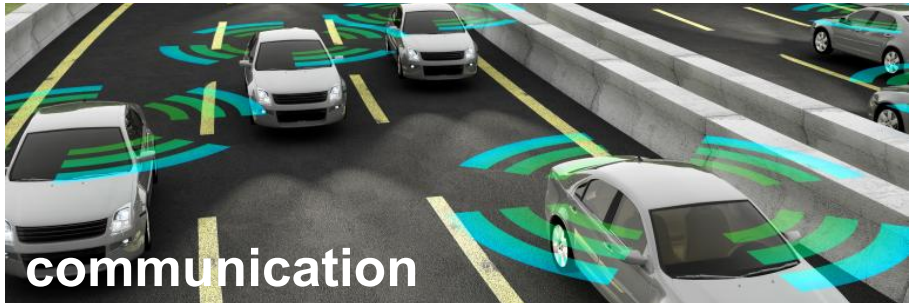


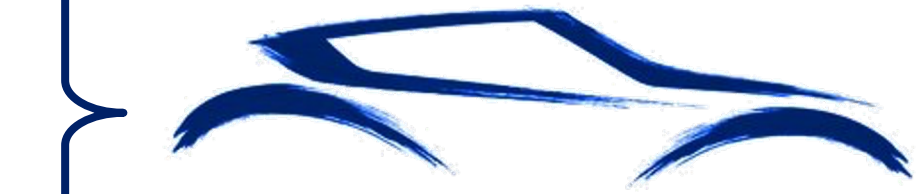


GSMA MOBILE WORLD CONGRESS
BARCELONA 22-25 FEB 2016

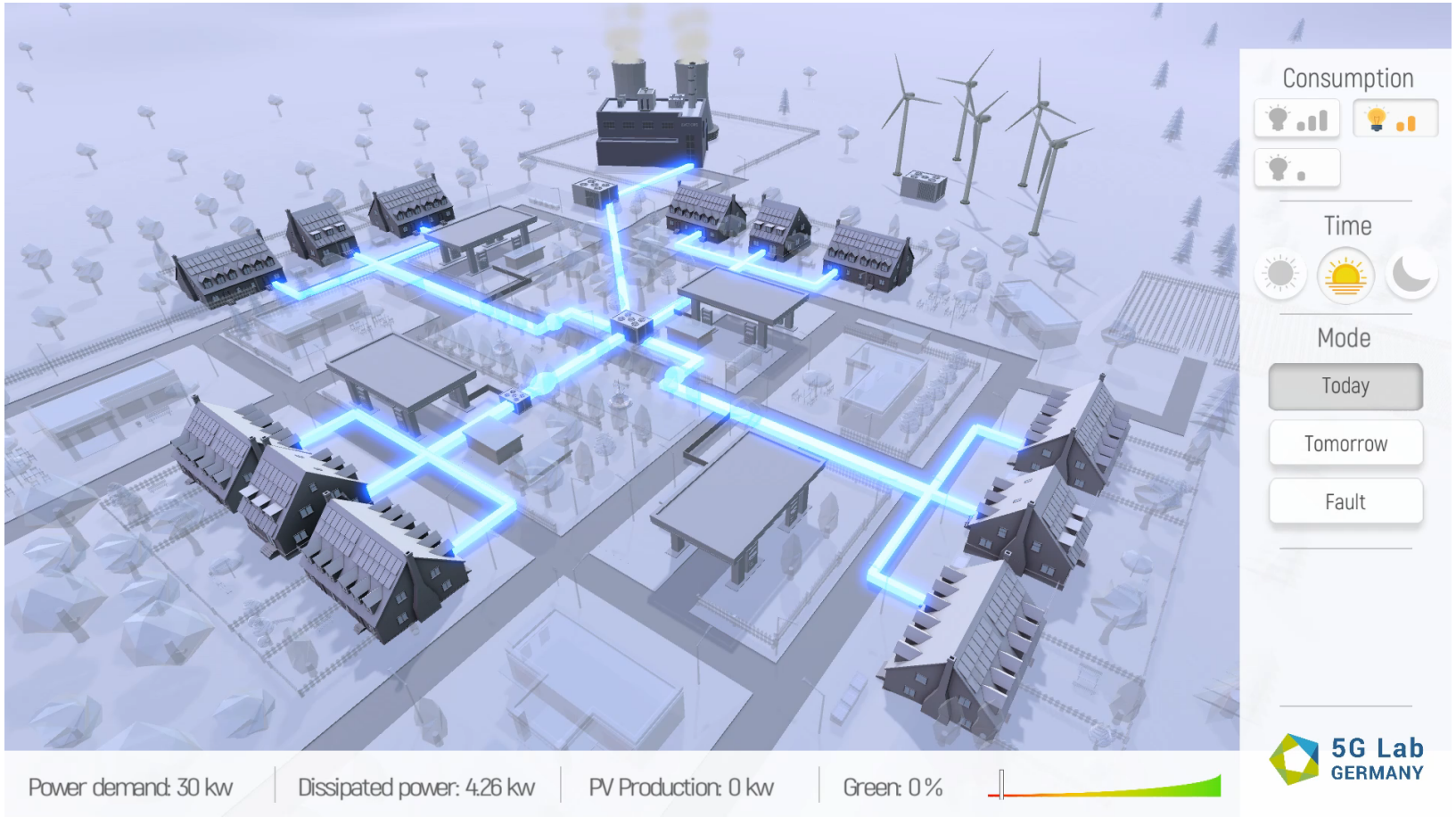
Digital Transfer





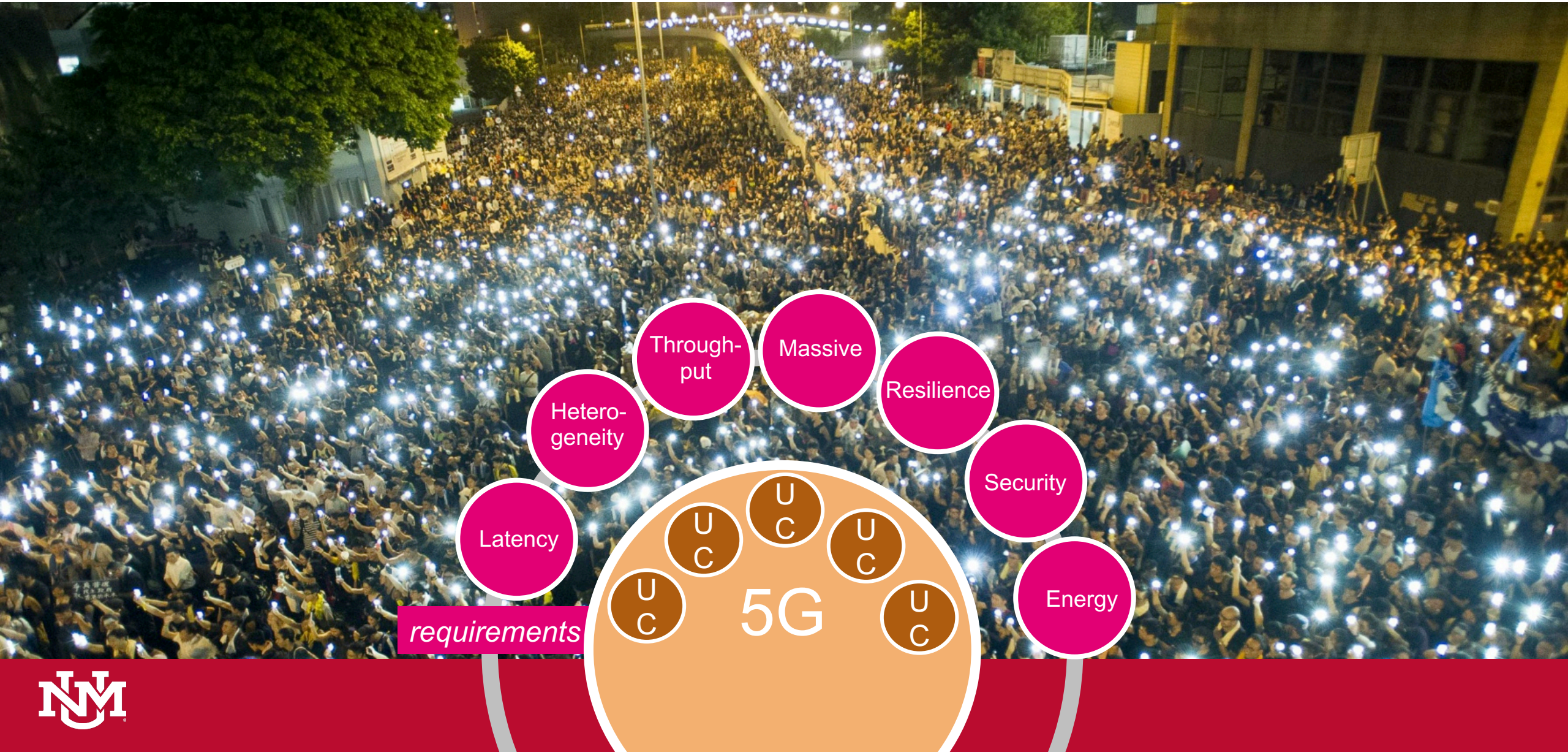


Connected car


Consumption
Time
Mode
Today
Tomorrow
Fault
5G Lab
GERMANY
Power demand: 30 kw
Dissipated power: 4.26 kw
PV Production: 0 kw
Green: 0 %

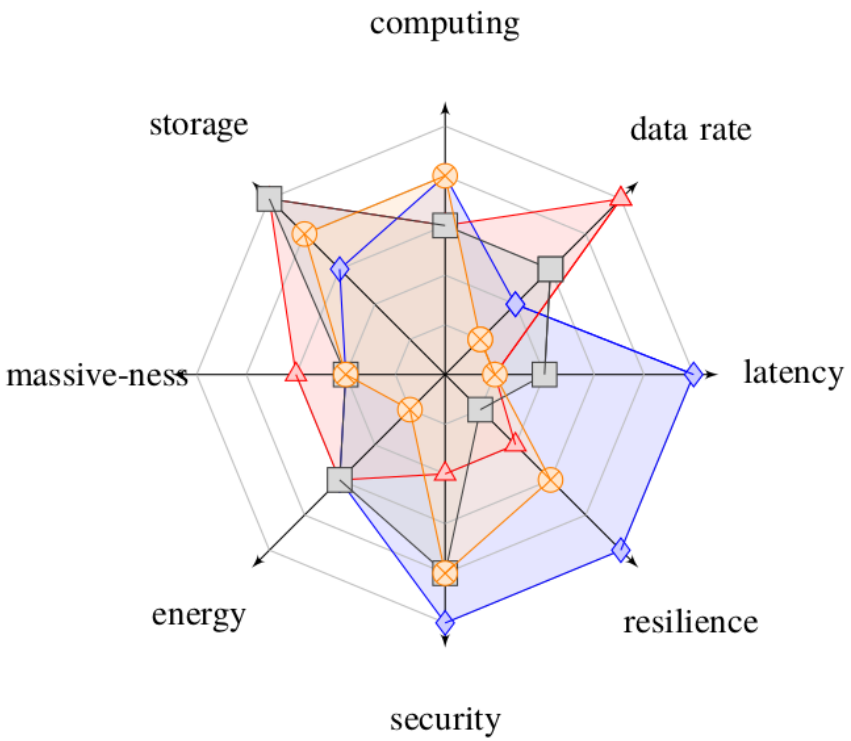
5G Technical Requirements

5G atom definition



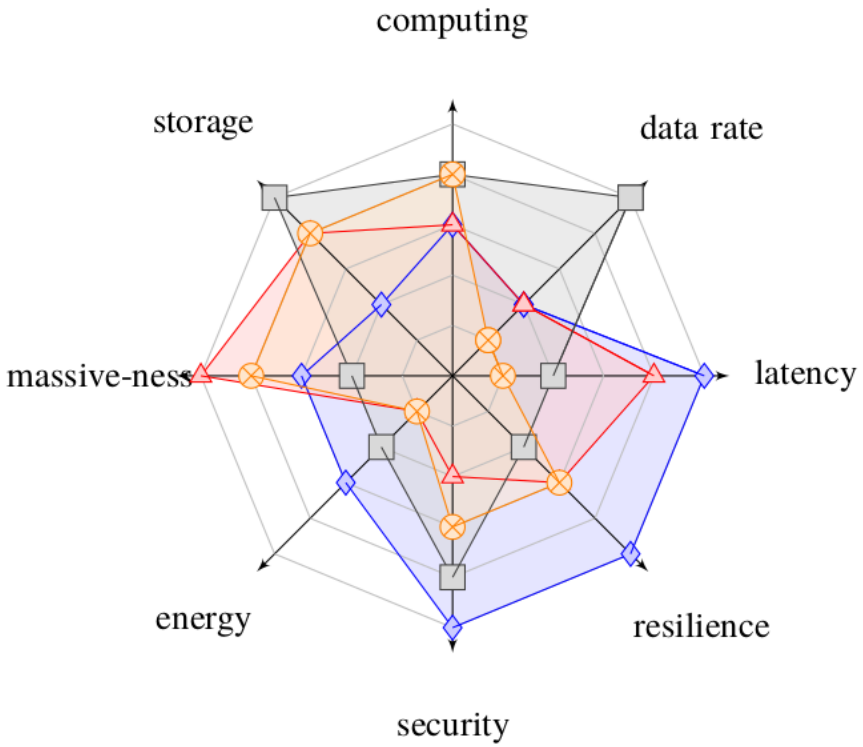
5G atom technical parameters and use cases

Connected Cars



◇ car control △ in-car entertainment
□ car navigation ⊗ predictive maintenance

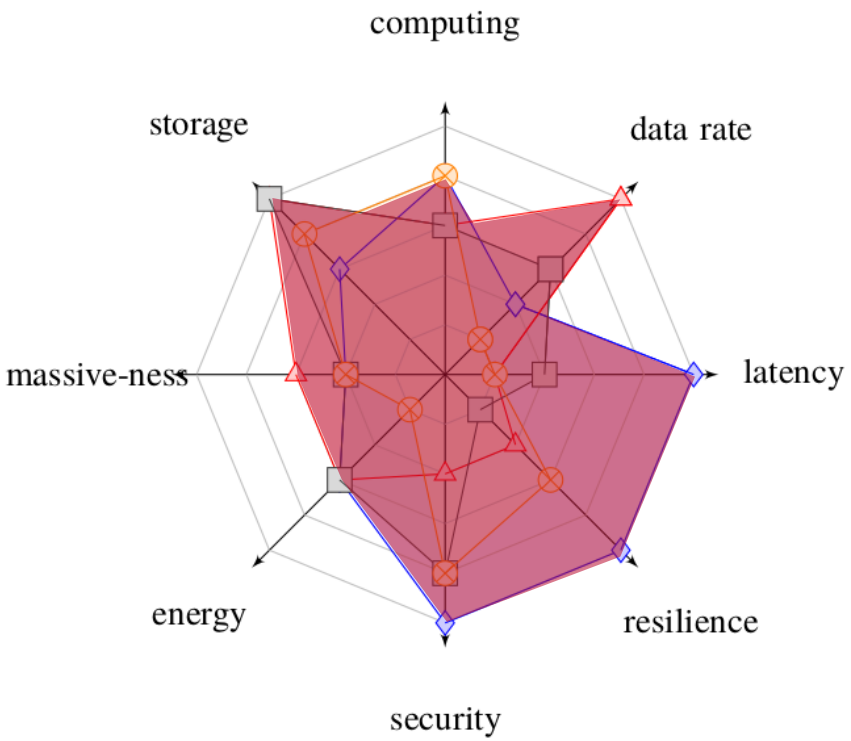
Industry 4.0



◇ machine control △ massive sensors
□ camera data ⊗ predictive maintenance

5G atom technical parameters and use cases

Connected Cars



◇ car control △ in-car entertainment
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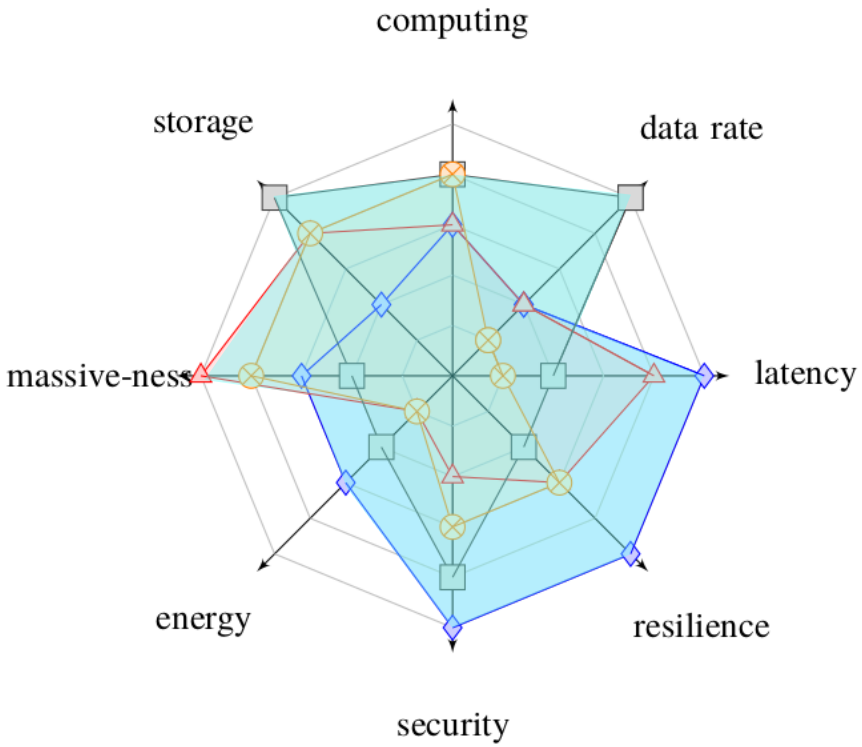
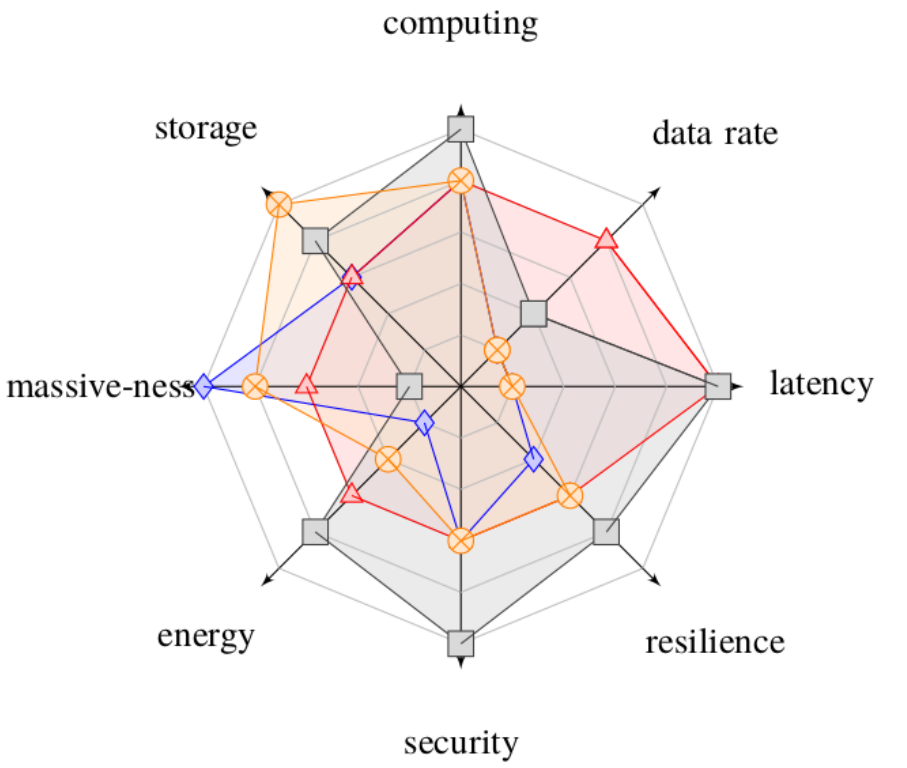
Industry 4.0



◇ machine control △ massive sensors
□ camera data ⊗ predictive maintenance

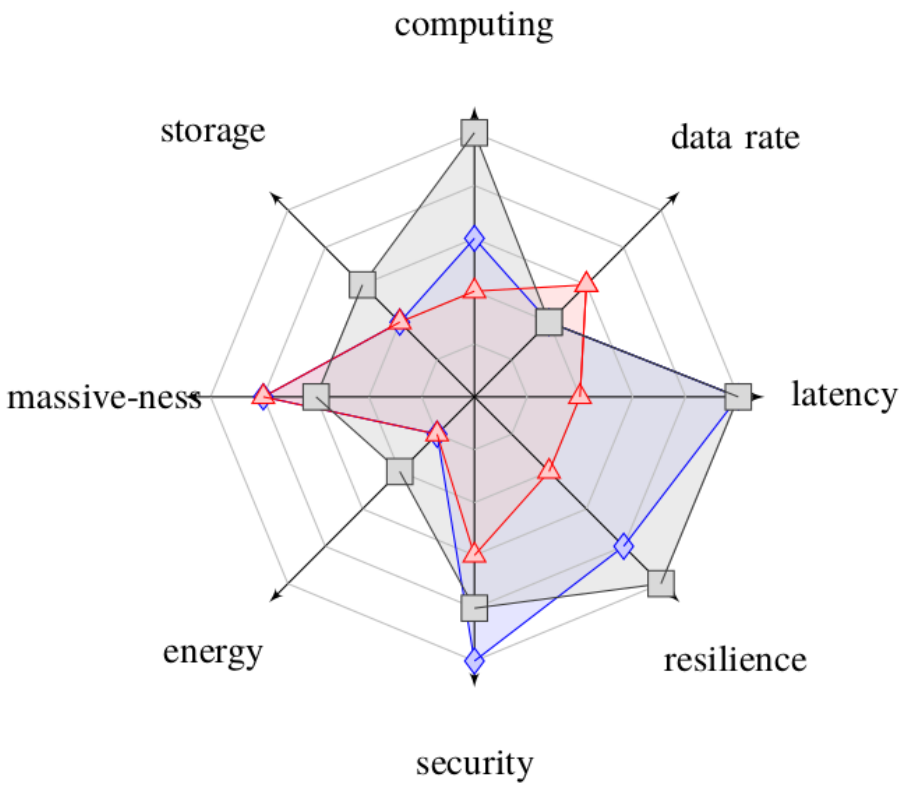
5G atom technical parameters and use cases

Farming



◇ ground sensing △ farm imaging
□ agricultural machine automation ⊗ predictive maintenance

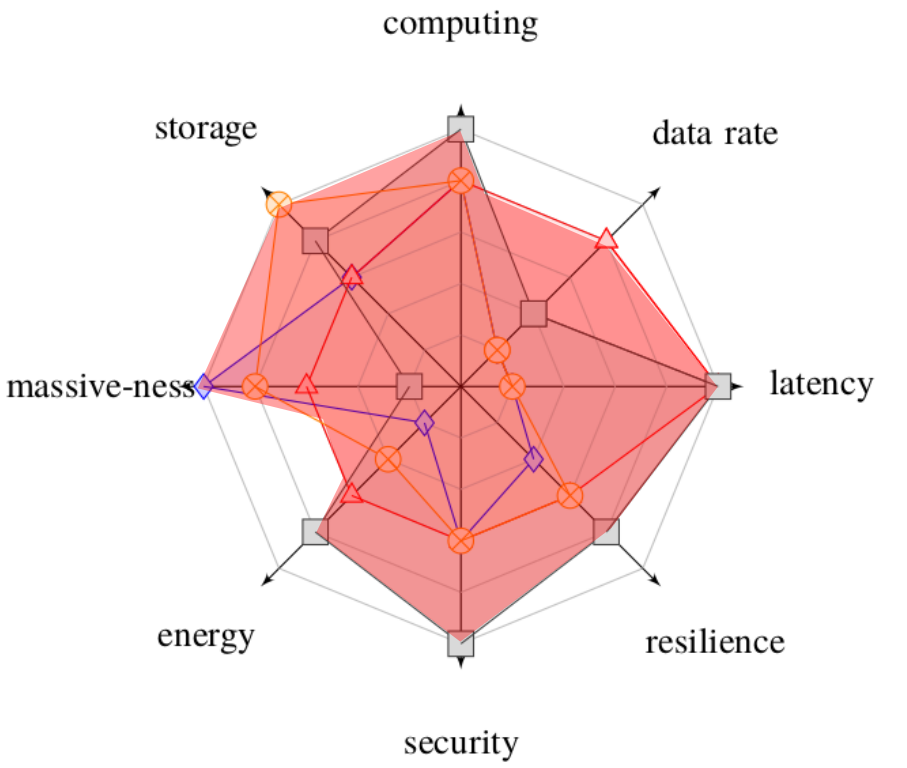
Smart Grids



◇ self organizing virtual power △ smart home □ fault detection

5G atom technical parameters and use cases

Farming



◇ ground sensing △ farm imaging
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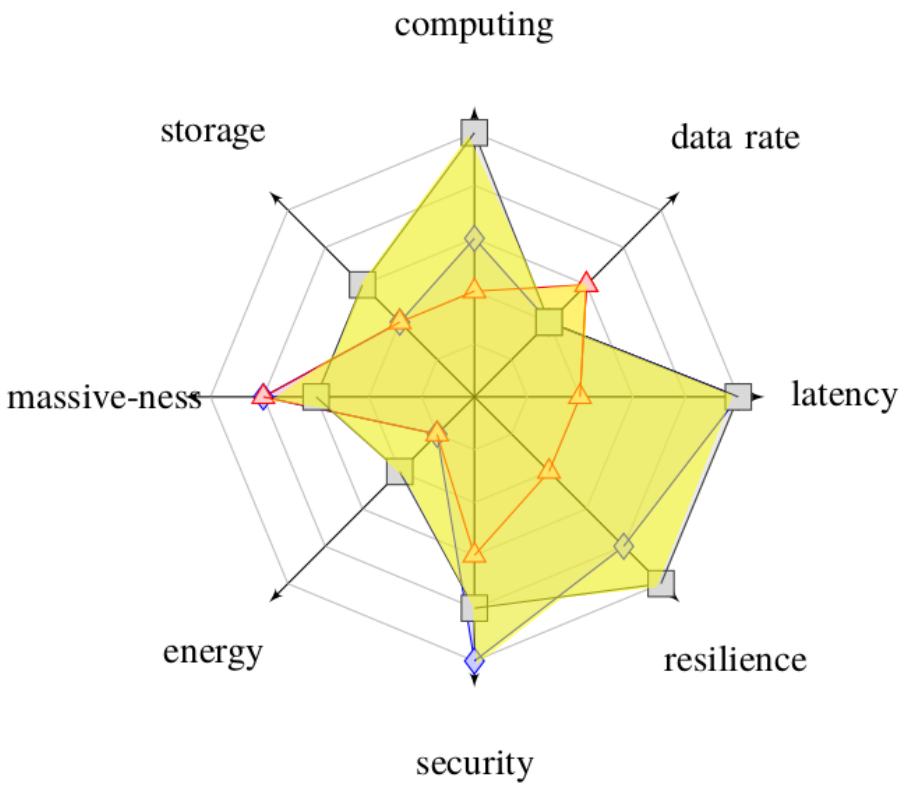
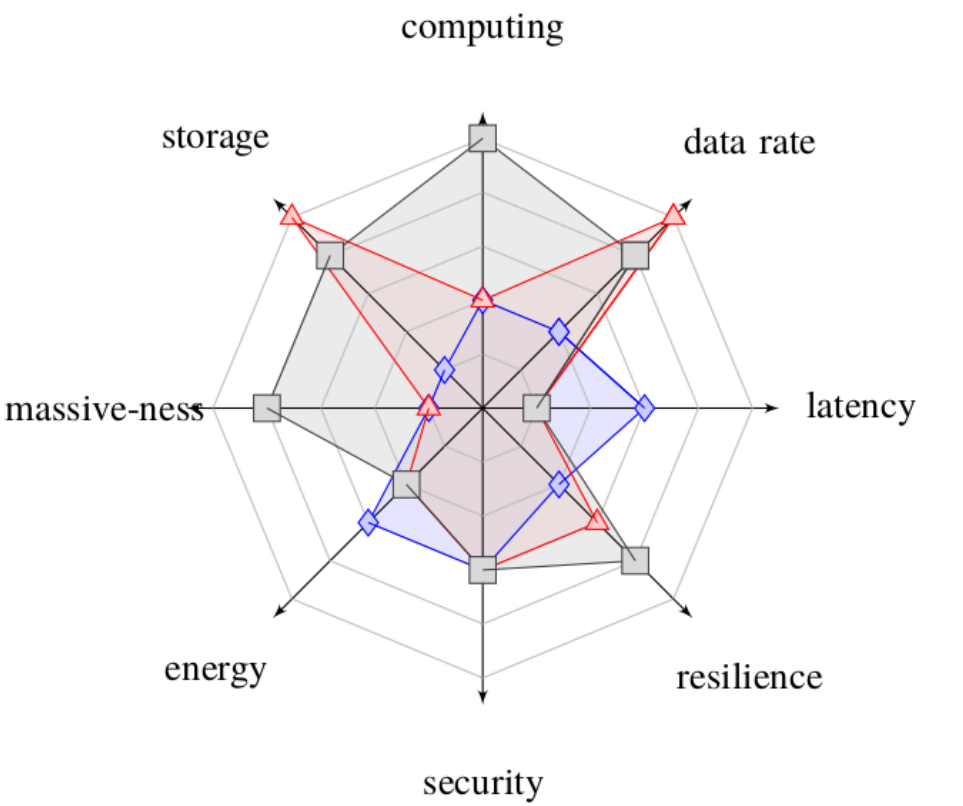
Smart Grids



◇ self organizing virtual power △ smart home □ fault detection

5G atom technical parameters and use cases

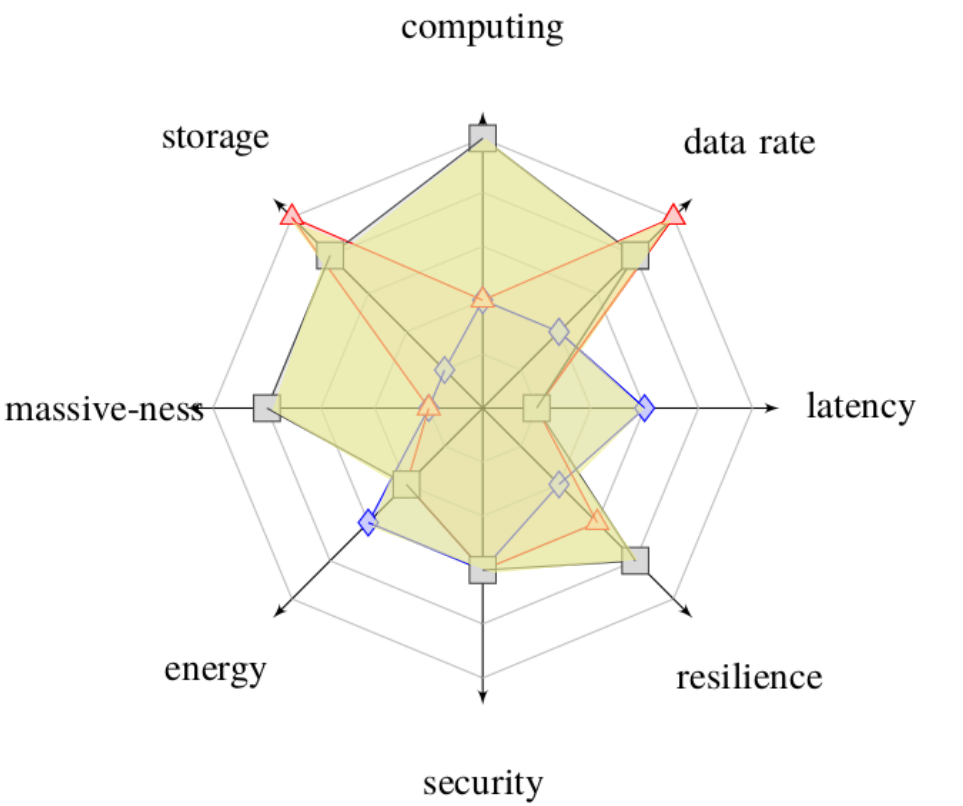
Tactile Internet



◇ human training △ skill transfer □ human-machine interaction

5G atom technical parameters and use cases

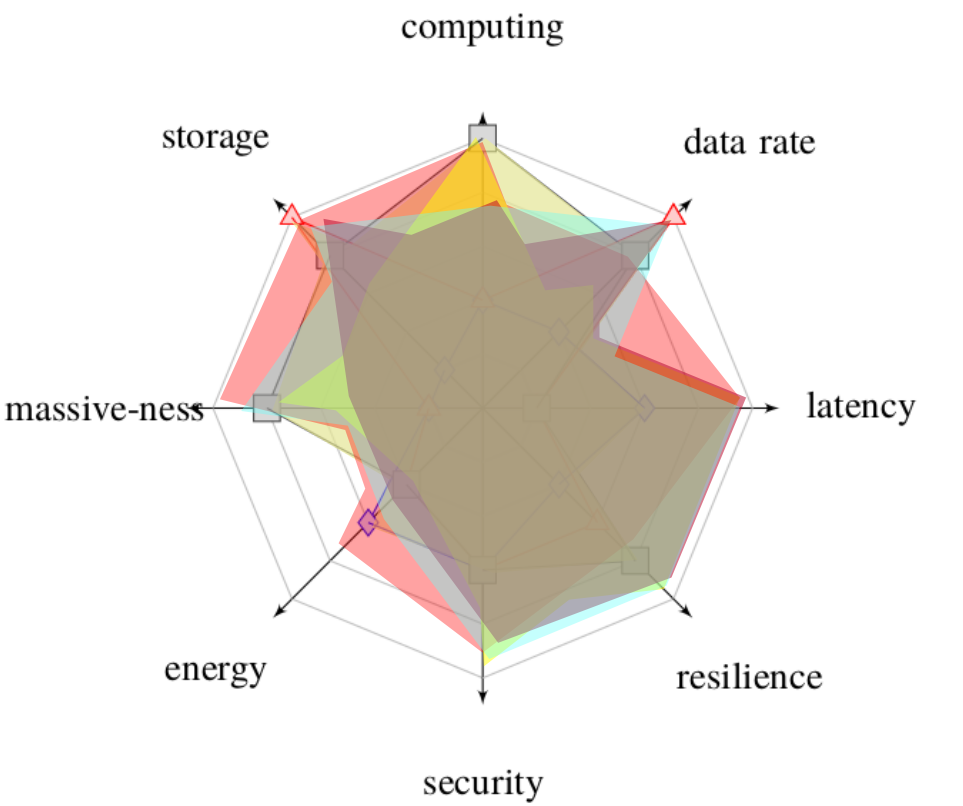
Tactile Internet



◇ human training △ skill transfer □ human-machine interaction

5G atom technical parameters and use cases

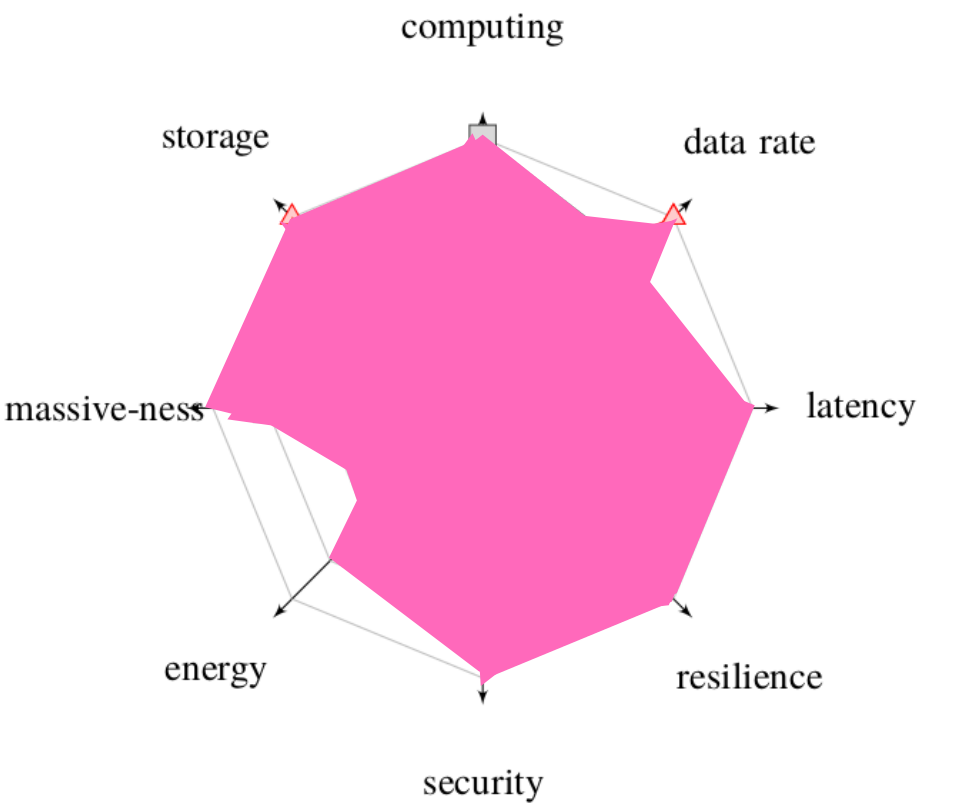
Tactile Internet



◇ human training △ skill transfer □ human-machine interaction

5G atom technical parameters and use cases

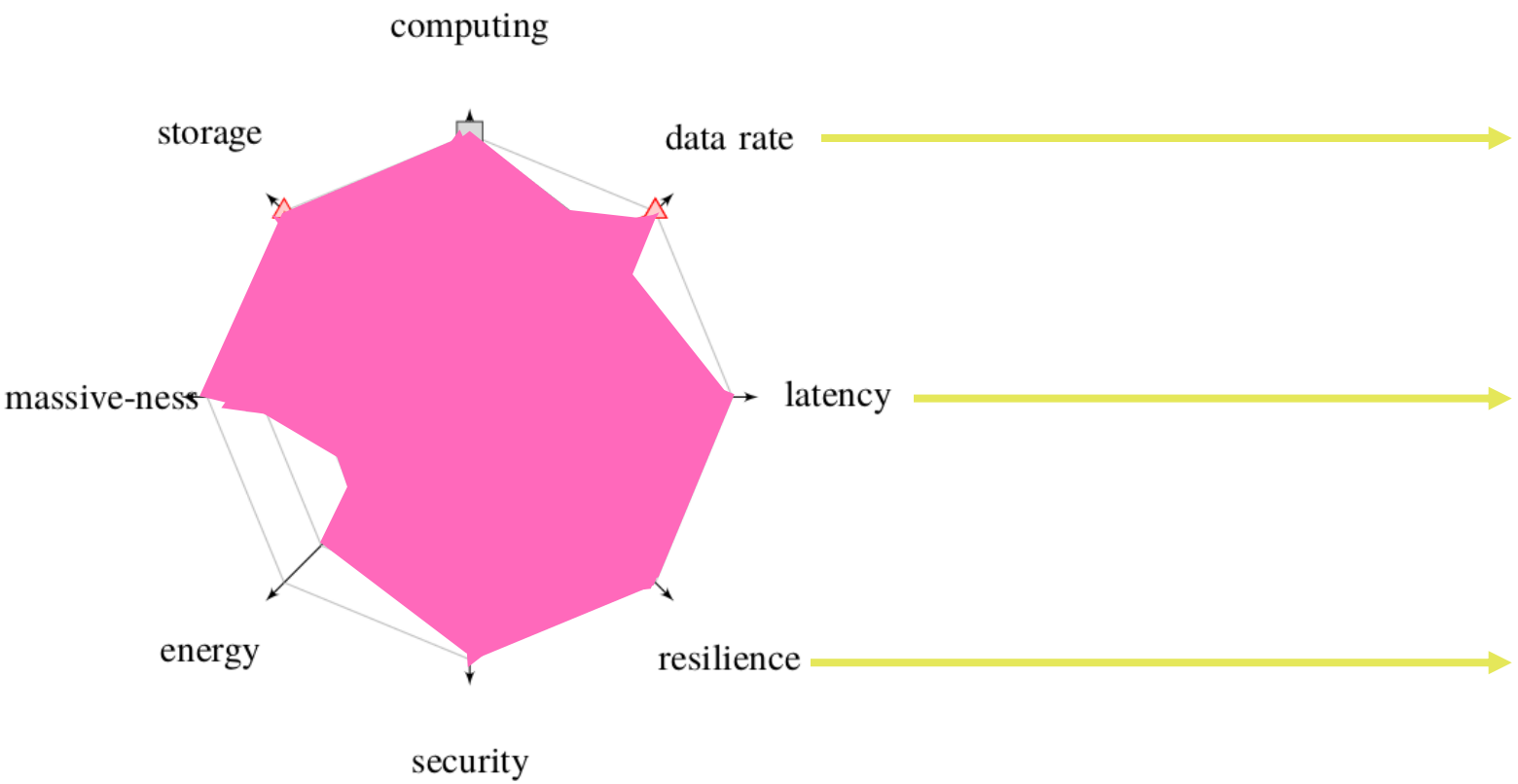
Tactile Internet



◇ human training △ skill transfer □ human-machine interaction

5G atom technical parameters and use cases

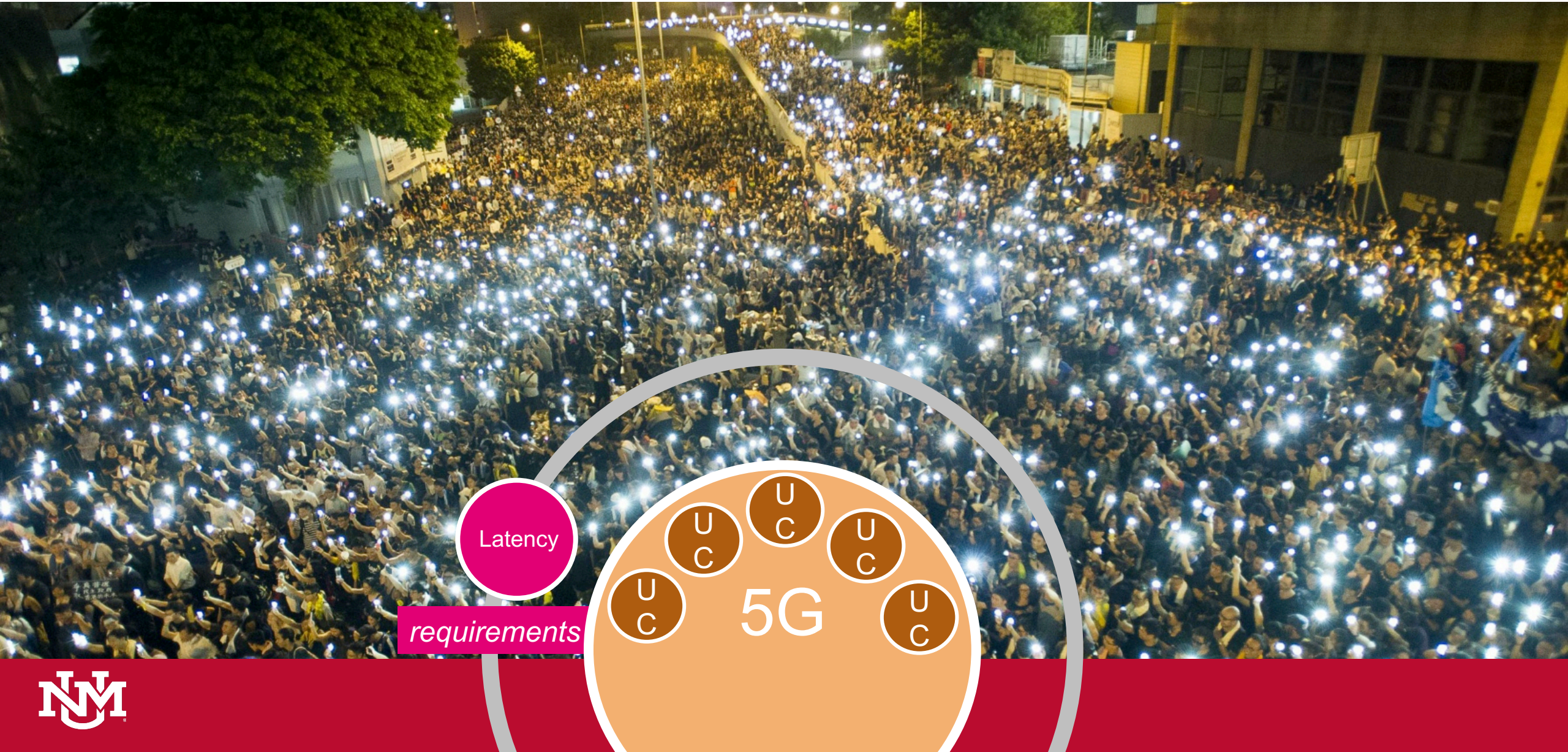
Tactile Internet



◇ human training △ skill transfer □ human-machine interaction

These three alone, how should this be realised?

5G atom definition



Achieving Low Latency

CeTI latency challenge (TU Munich – Prof. Steinbach)

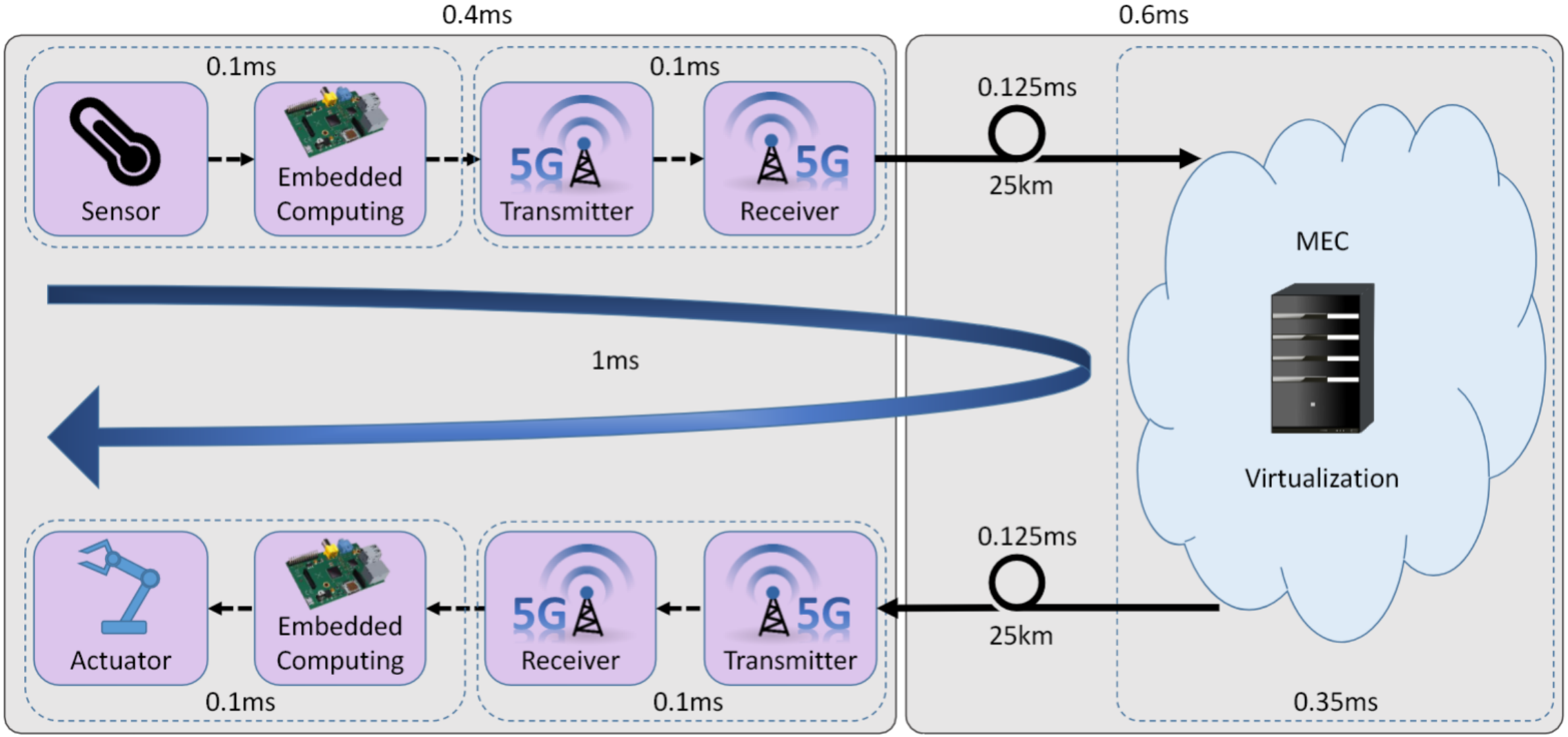
Latency constraints for bilateral (closed-loop) haptic communication

Simulated network delay

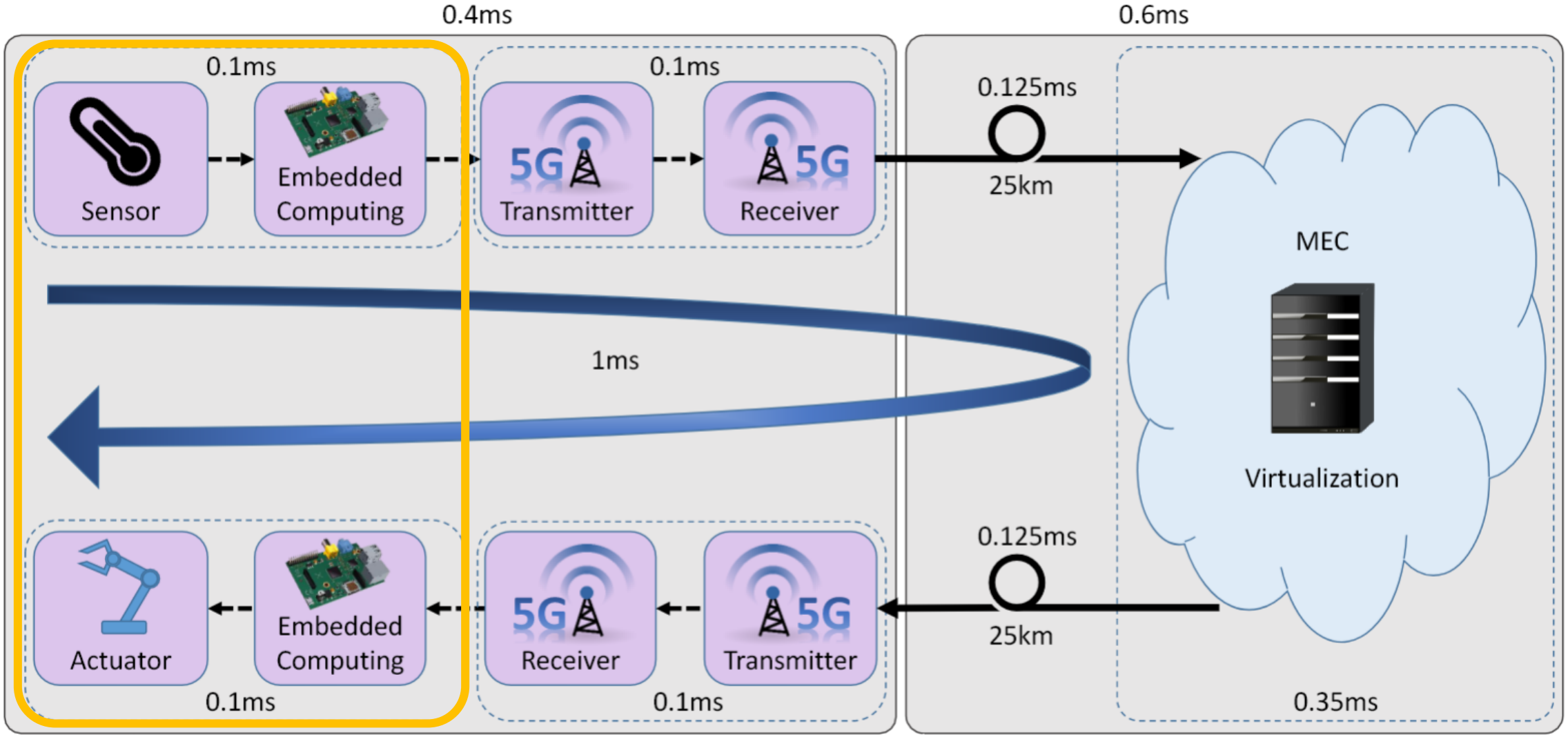
CeTI latency challenge

Impact of latency on task performance and learning (here: 40 ms LTE network latency one way)

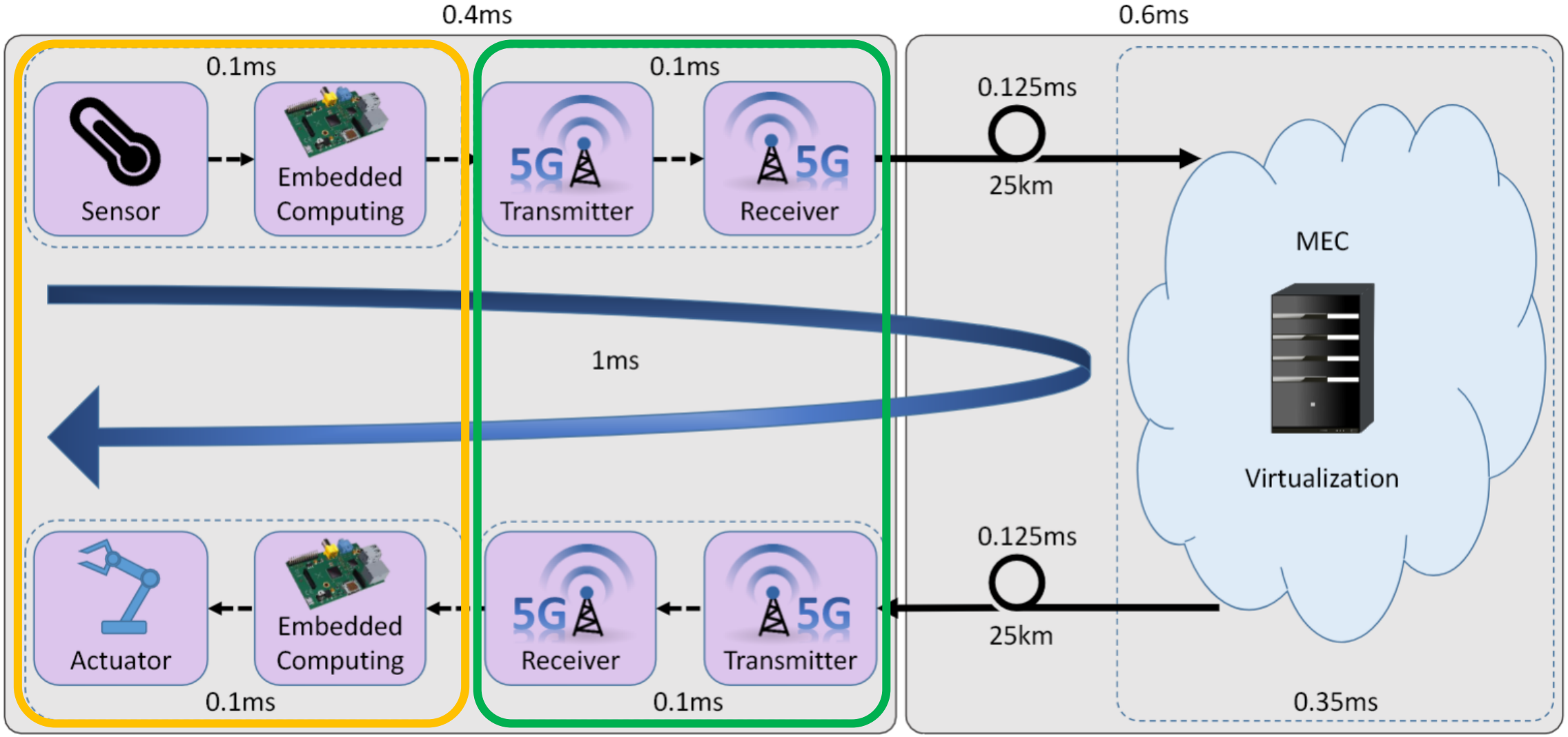
5G atom definition



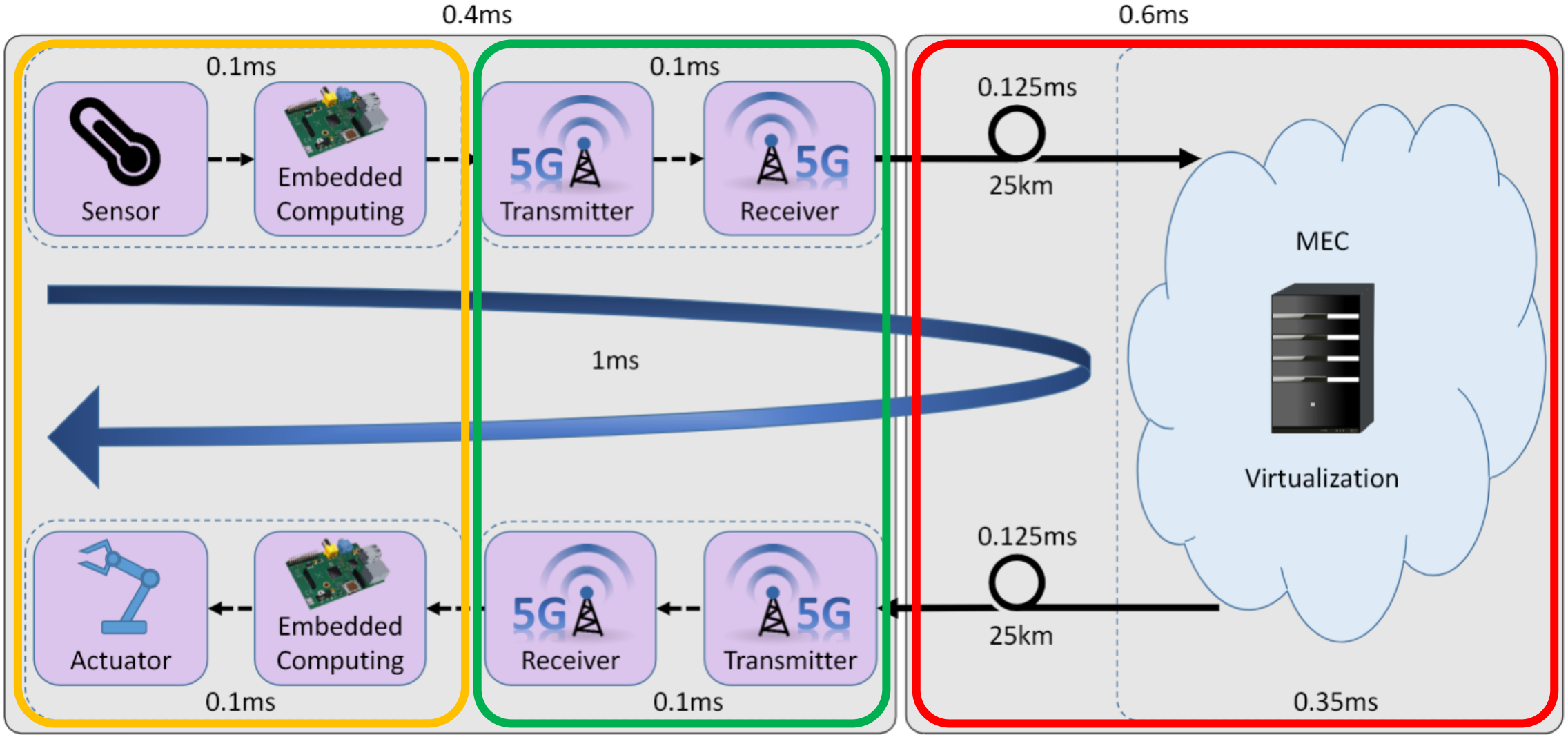
5G atom definition



5G atom definition



5G atom definition



Latency definition: General view

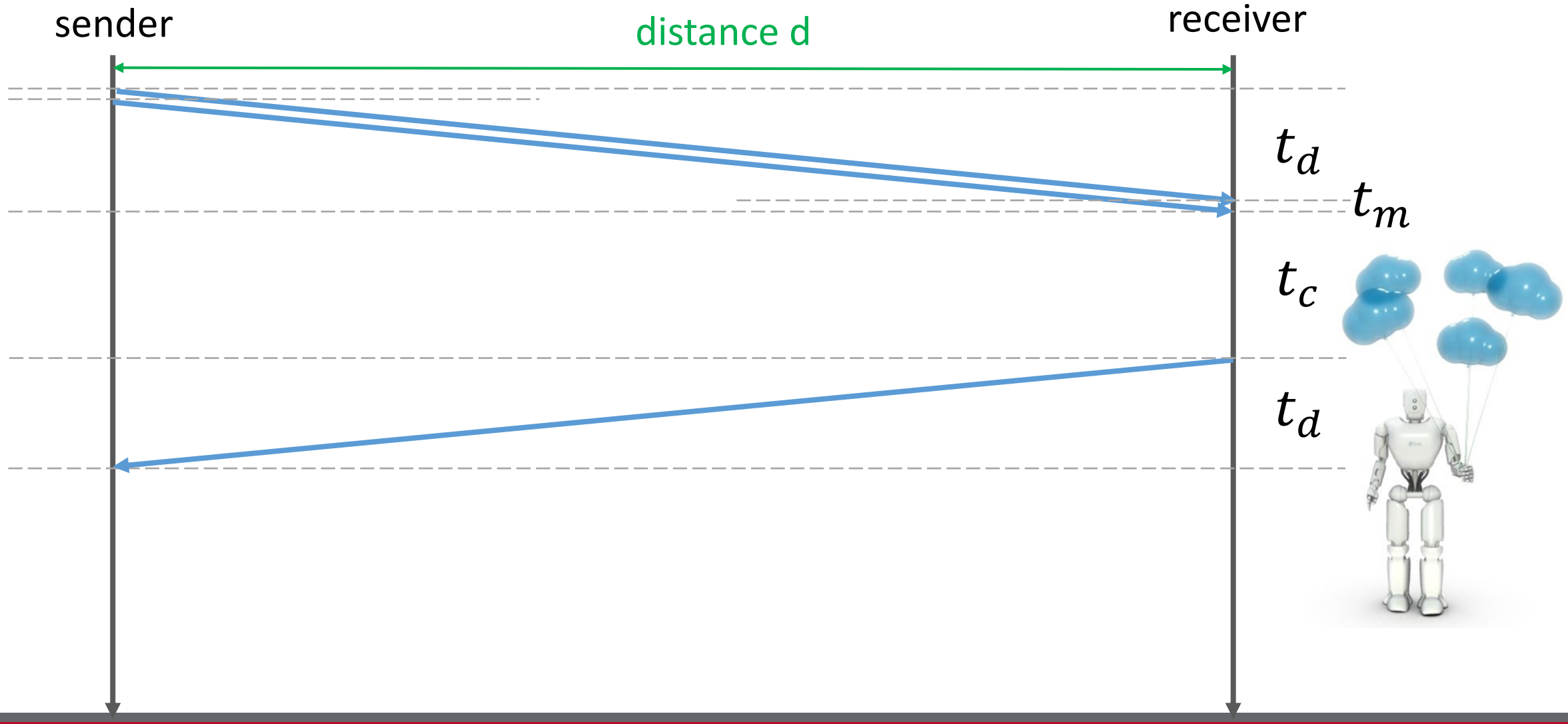
$$t_d = \frac{d}{vc}$$

$$t_m = \frac{L}{R}$$

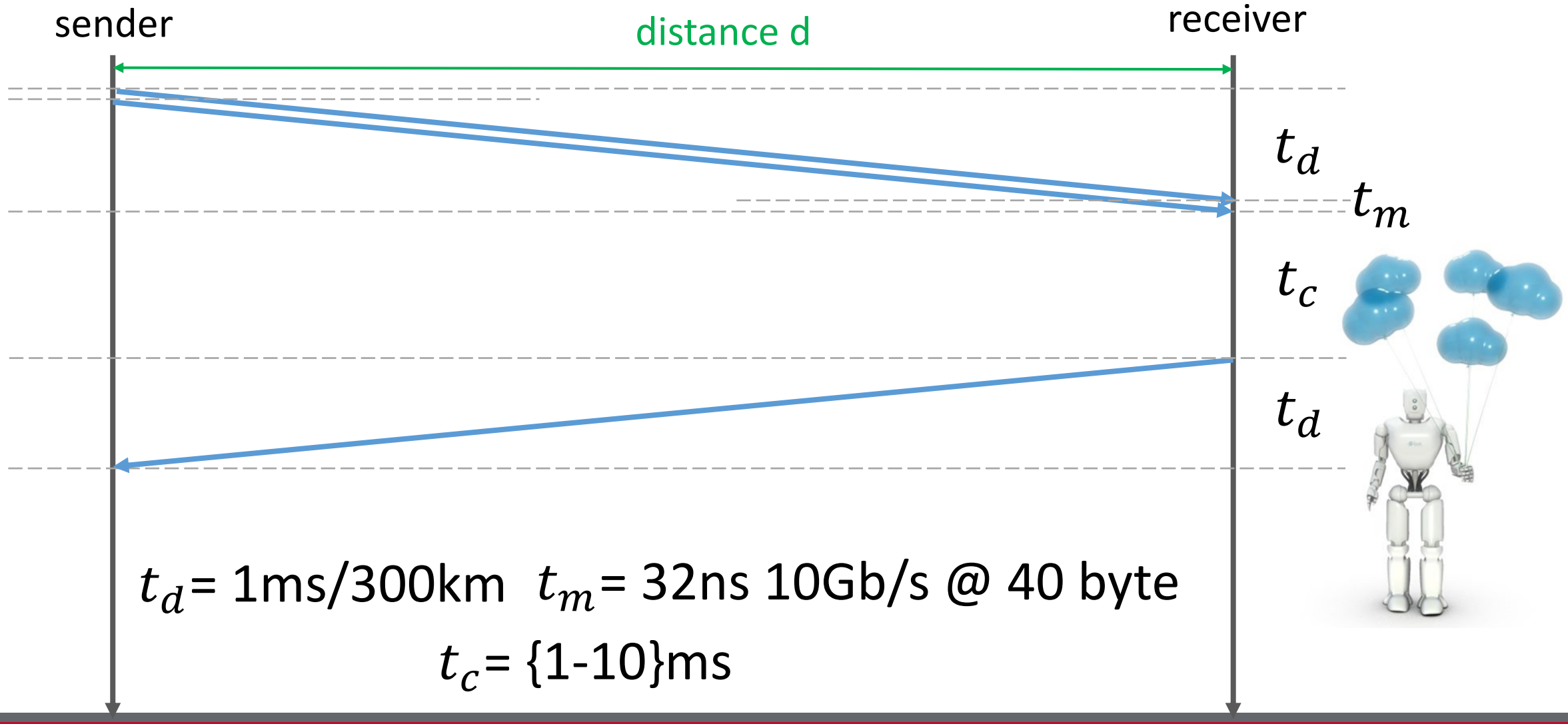
$$t_c$$

$$t_d = \frac{d}{vc}$$

Latency definition: Data rate is not the problem



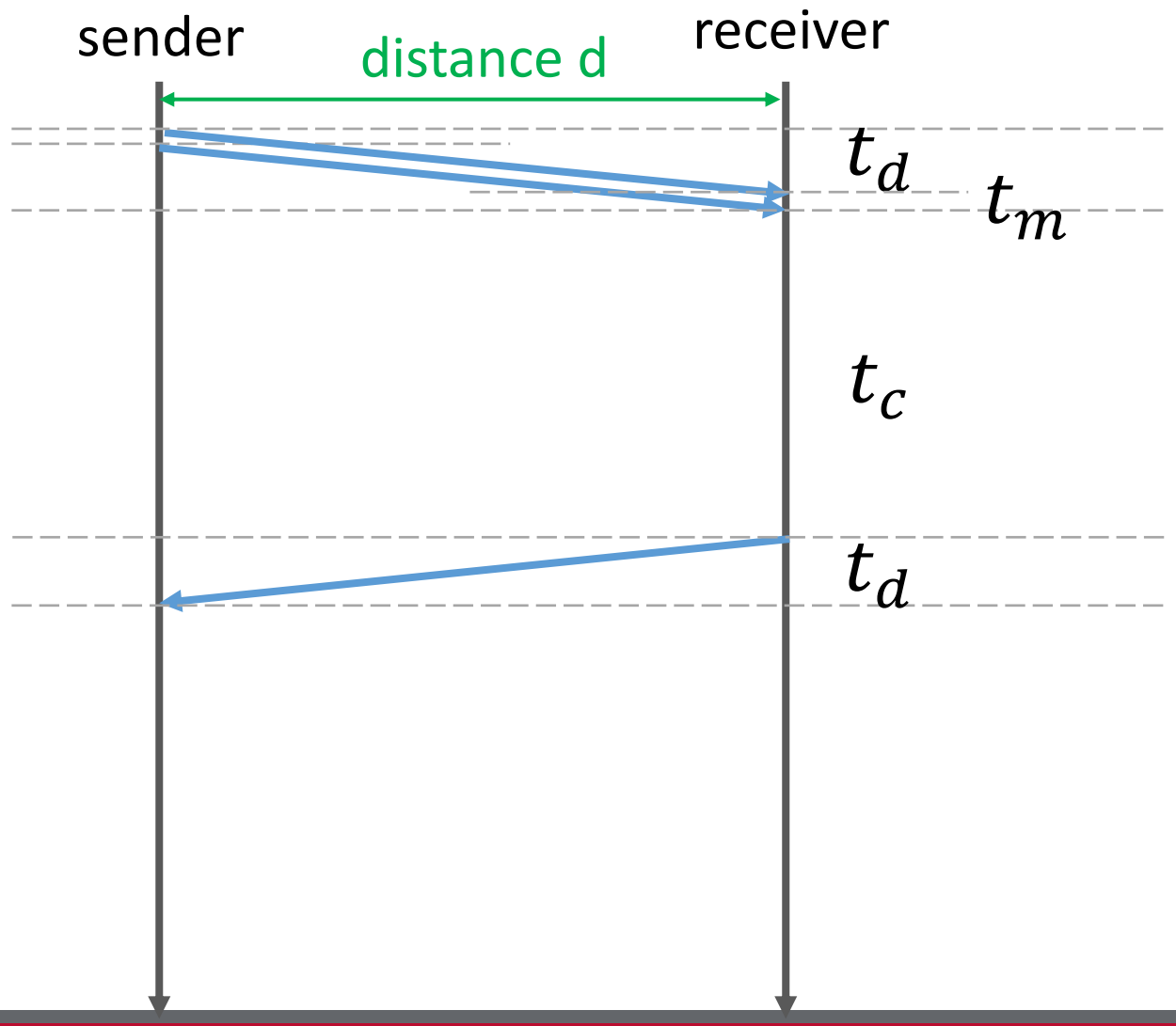
Latency definition: Data rate is not the problem

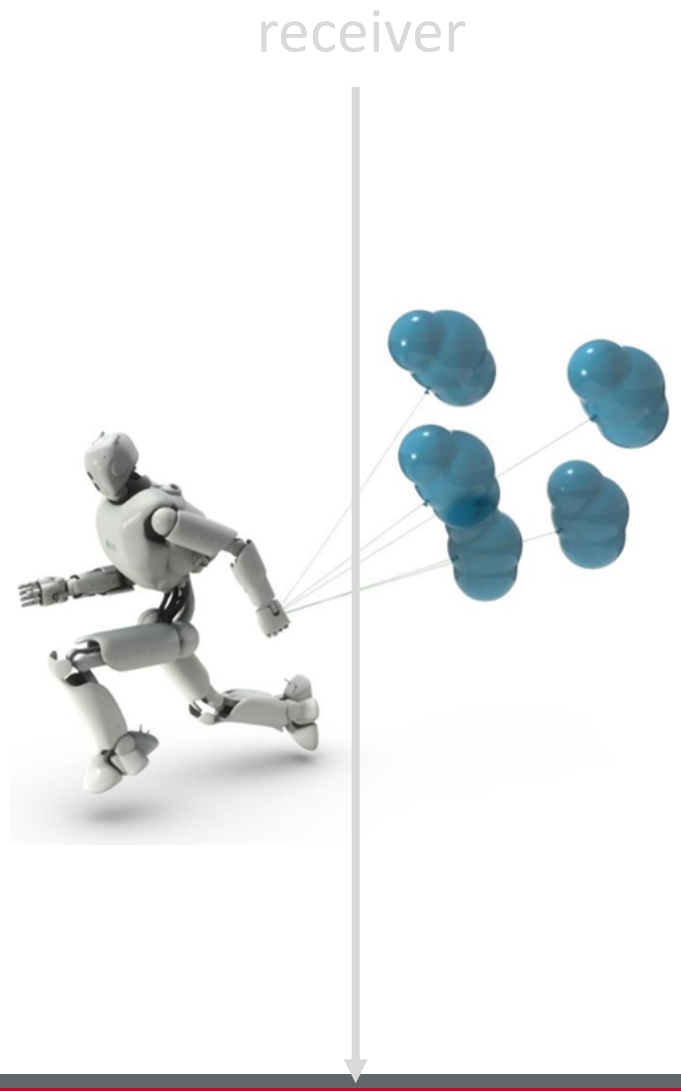


t_d= 1ms/300km t_m= 32ns 10Gb/s @ 40 byte

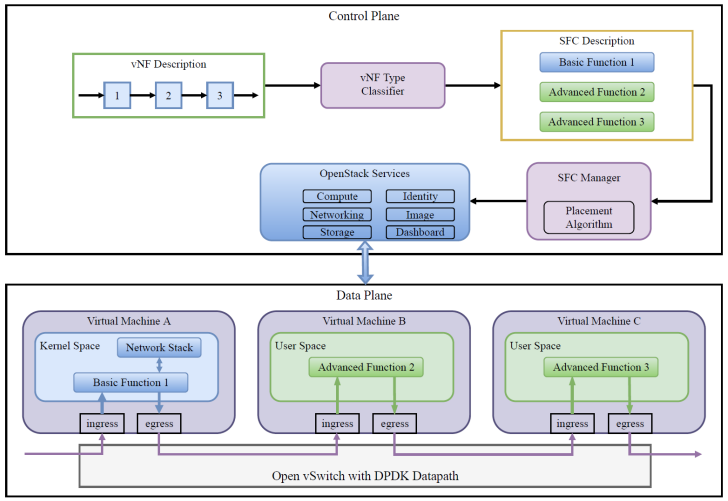
t_c= {1-10}ms

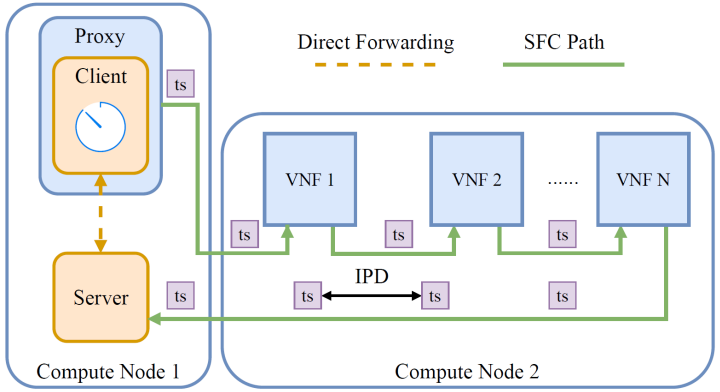
Latency definition: Advantage of the mobile edge

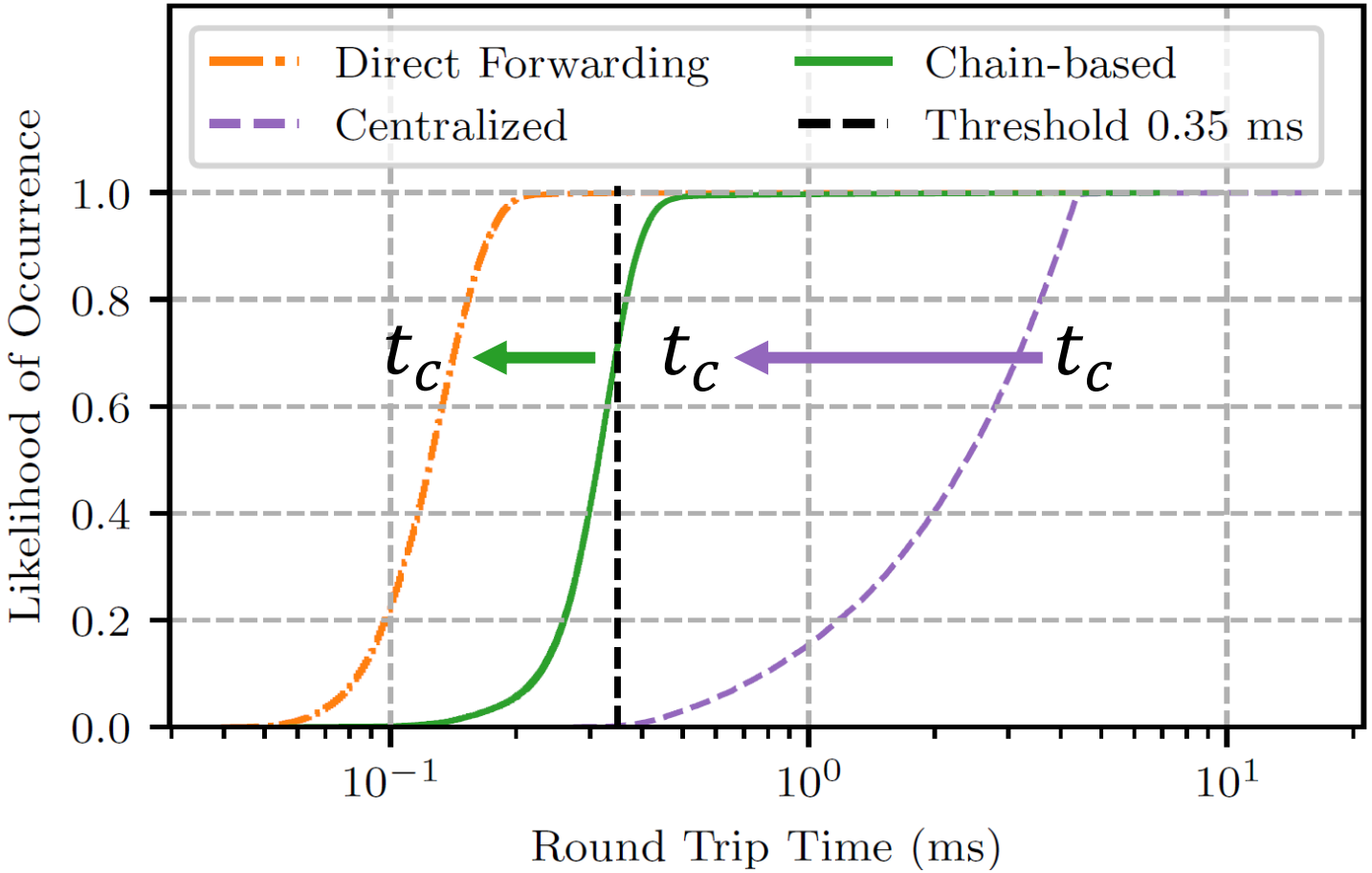




Latency definition: Softwarization

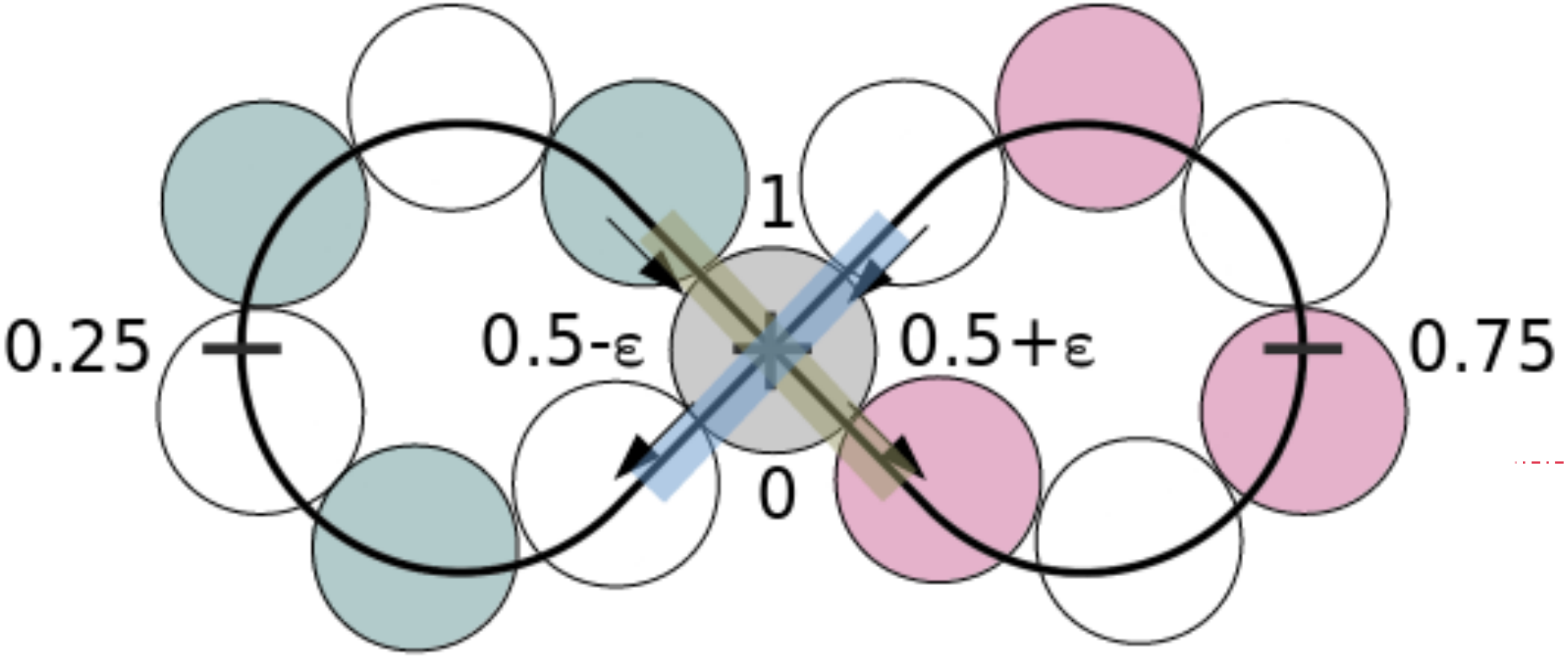




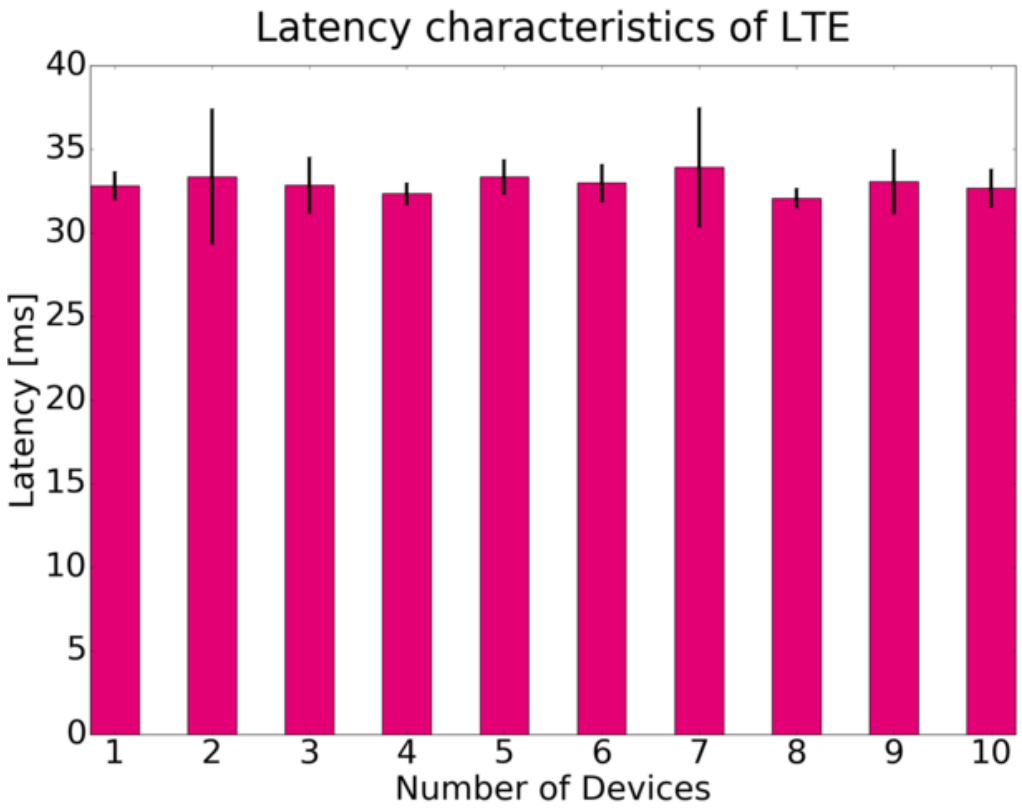


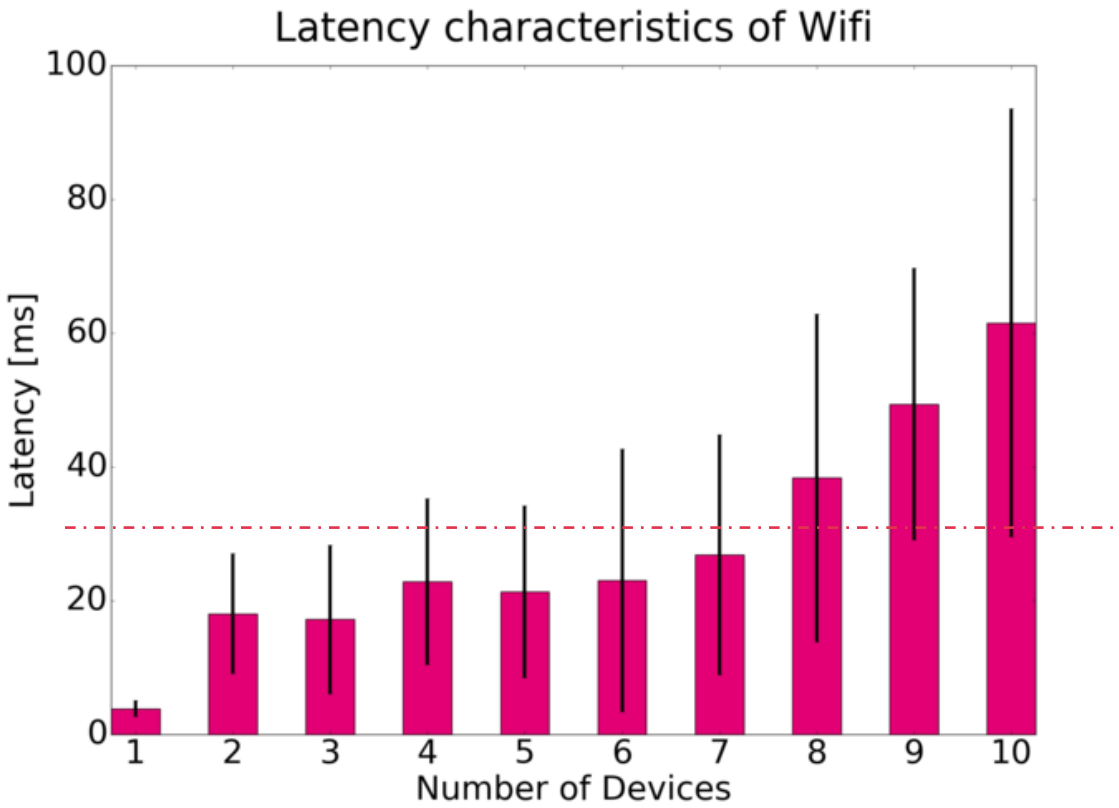
Zuo Xiang; Frank Gabriel; Elena Urbano; Giang T. Nguyen; Martin Reisslein; Frank H. P. Fitzek
Reducing Latency in Virtual Machines Enabling Tactile Internet for Human Machine Co-working Journal Article
IEEE Journal on Selected Areas in Communications, 37 (5), pp. 1098-1116, 2019, ISSN: 0733-8716.

Impact of Latency on Efficiency

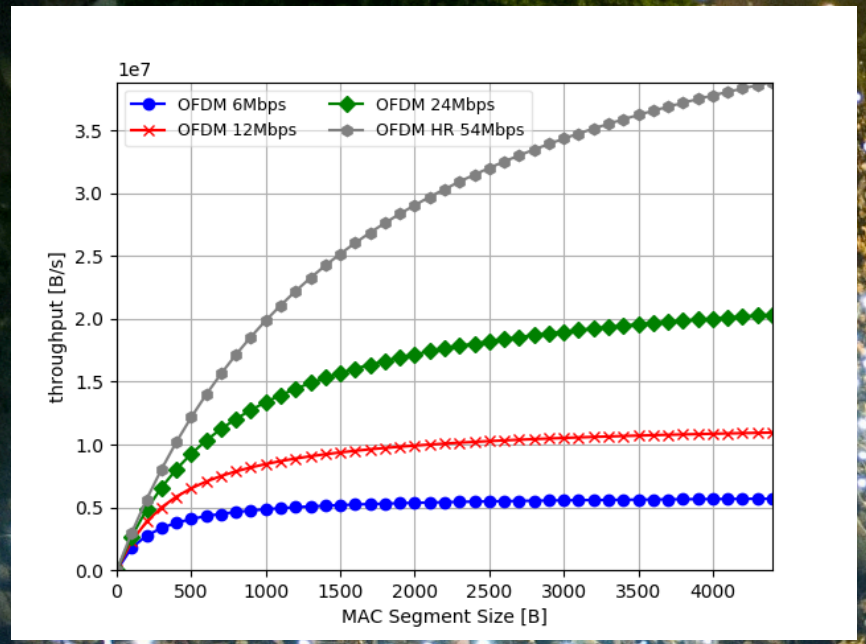


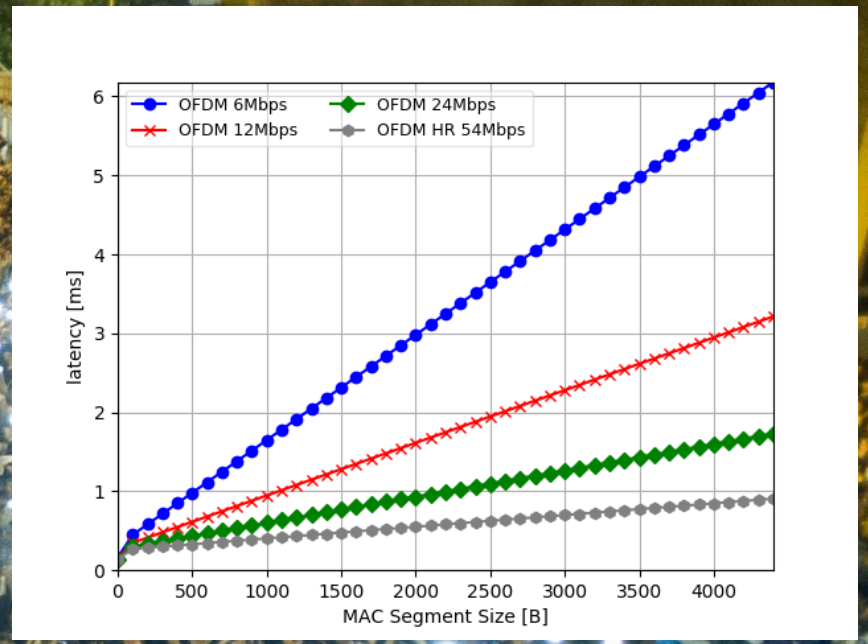
SoA Latency Values

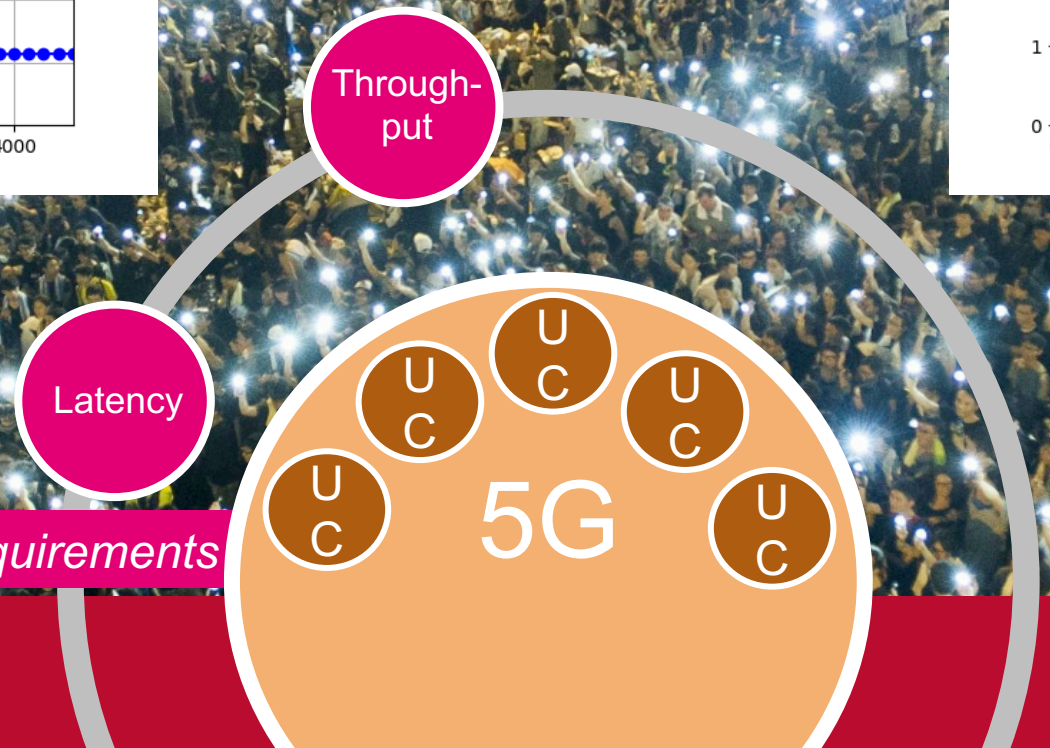




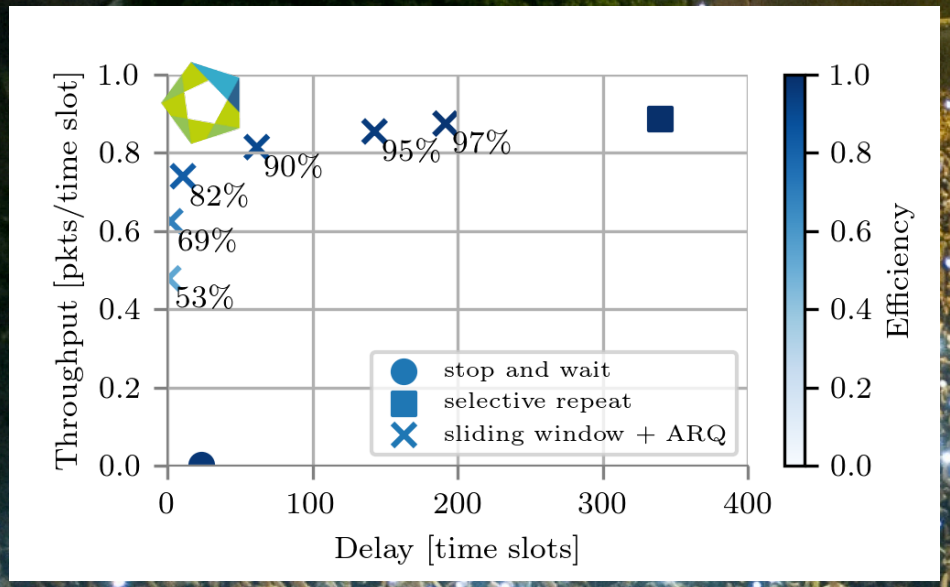
5G atom definition

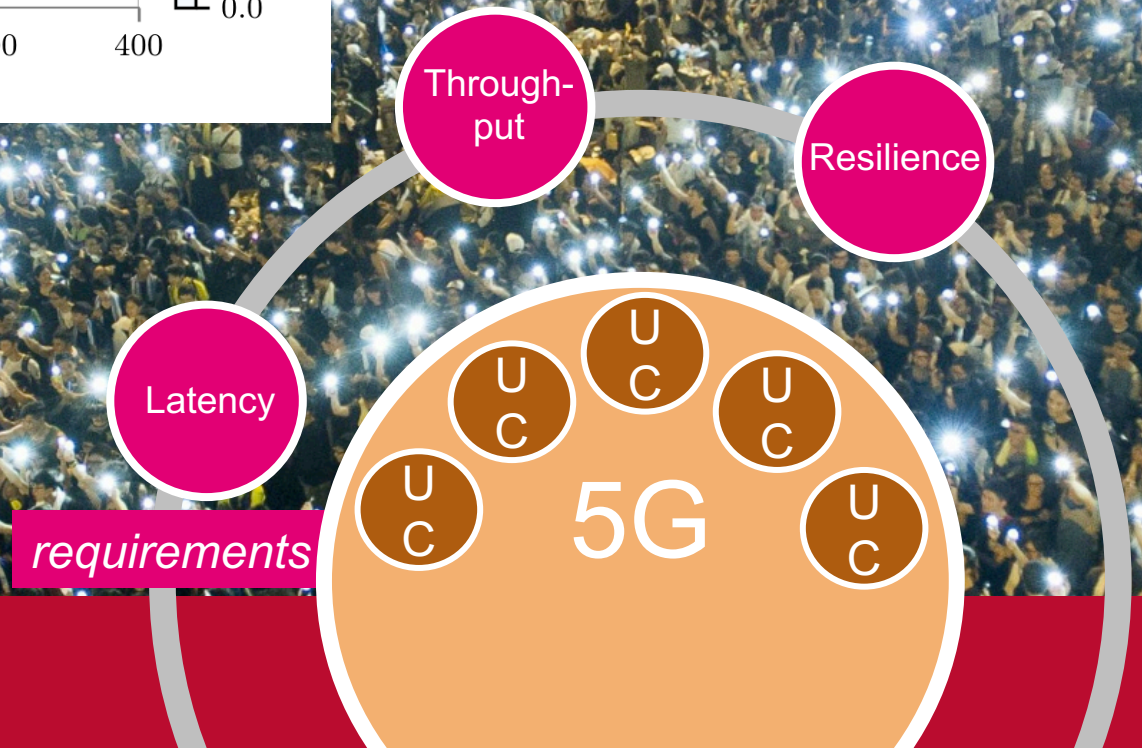






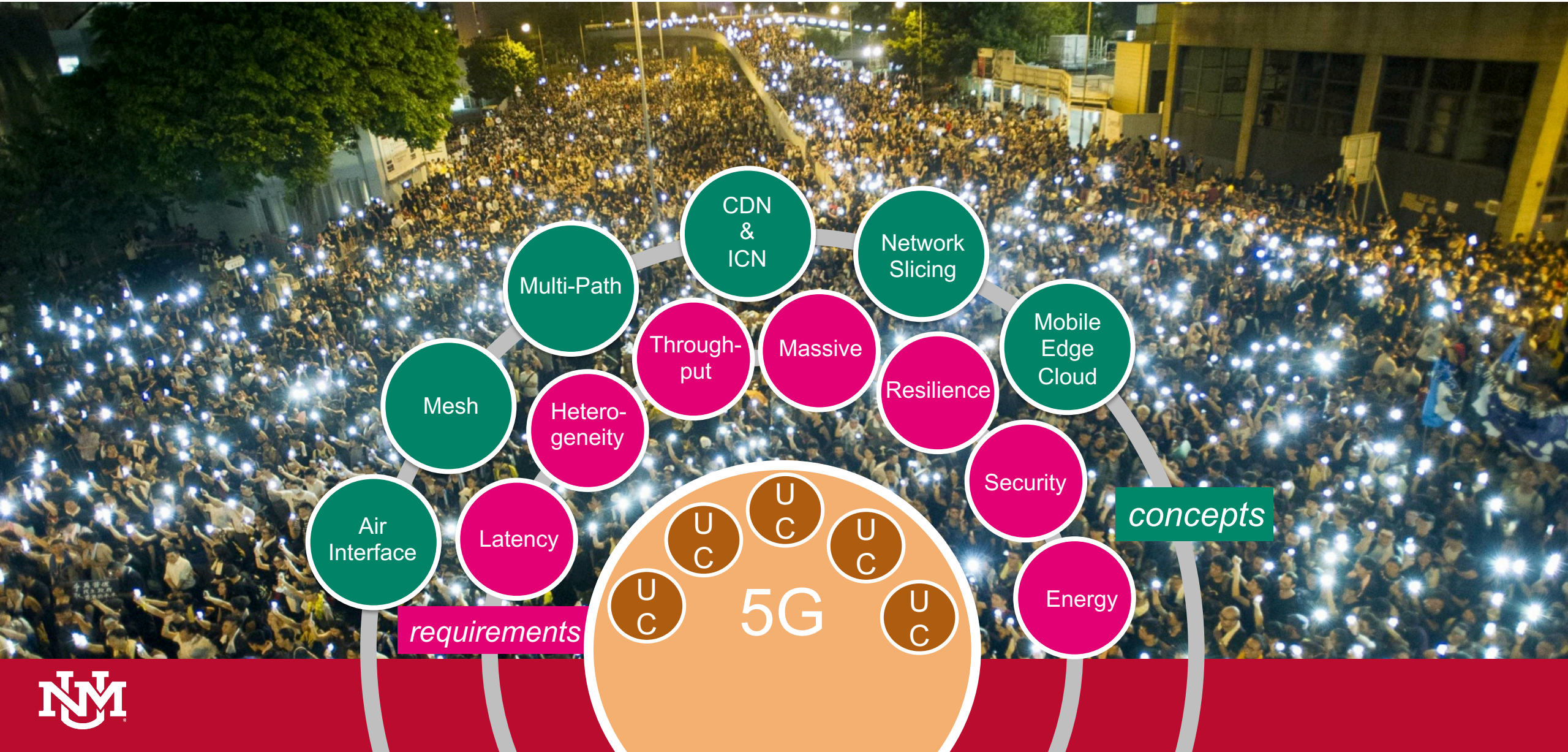
5G atom definition





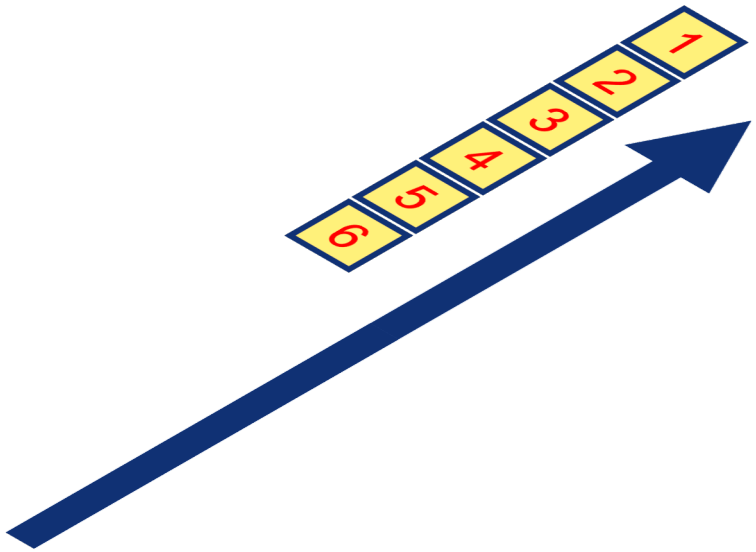
5G Concepts

5G atom definition



5G Concepts: Multi-Path

Multi-Path Explanation



Single Path

Throughput

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Resilience

[redacted]

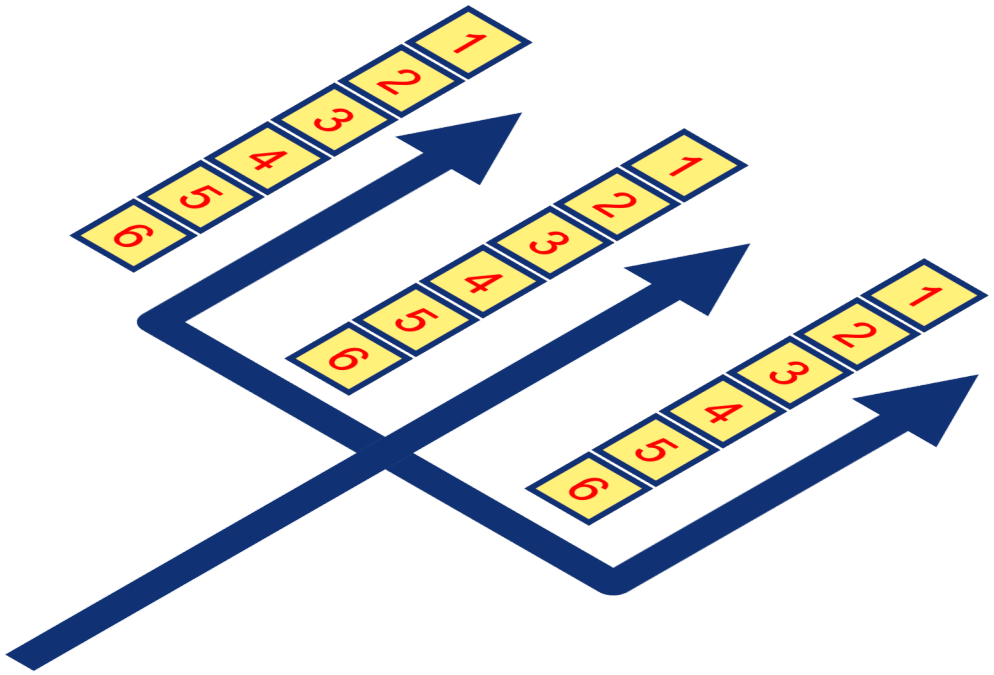
Security

[redacted]

Latency

[redacted]

Multi-Path Explanation



Multi-Path

Replication

Throughput

[redacted]

Resilience

[redacted]

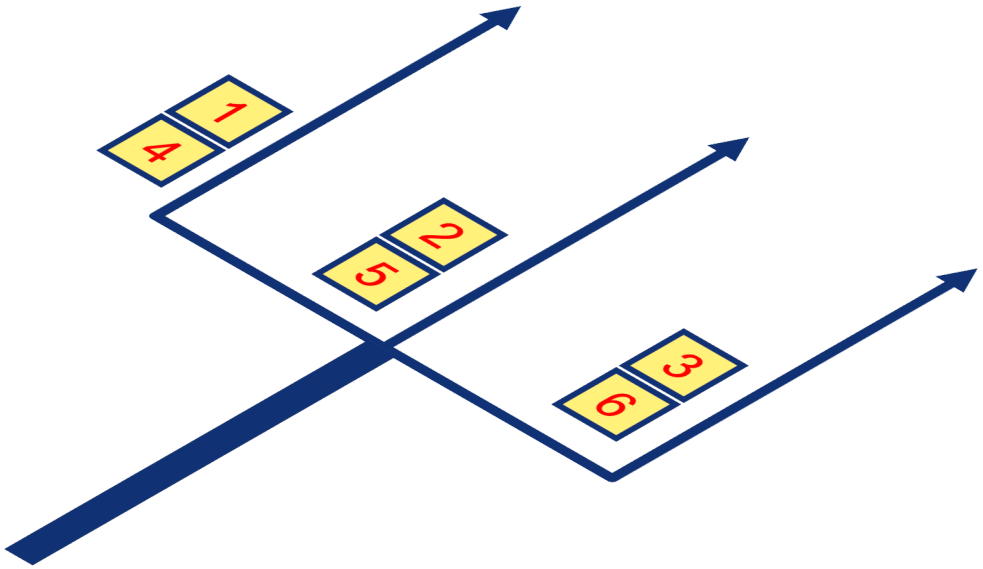
Security

[redacted]

Latency

[redacted]

Multi-Path Explanation



Multi-Path

Splitting

Throughput

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Resilience

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Security

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Latency

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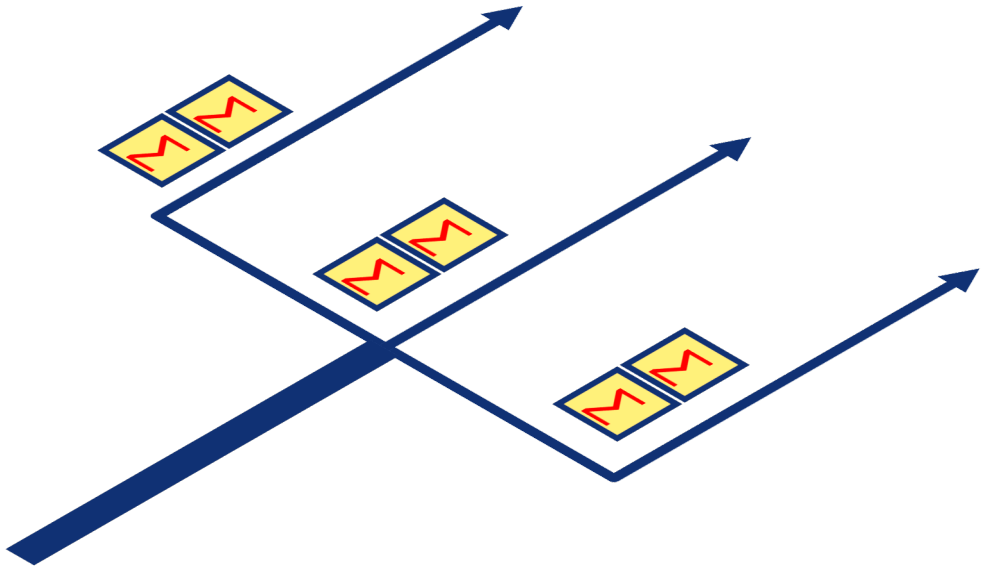
Multi-Path Explanation



Multi-Path

Coding

Throughput

[redacted]

Resilience

[redacted]

Security

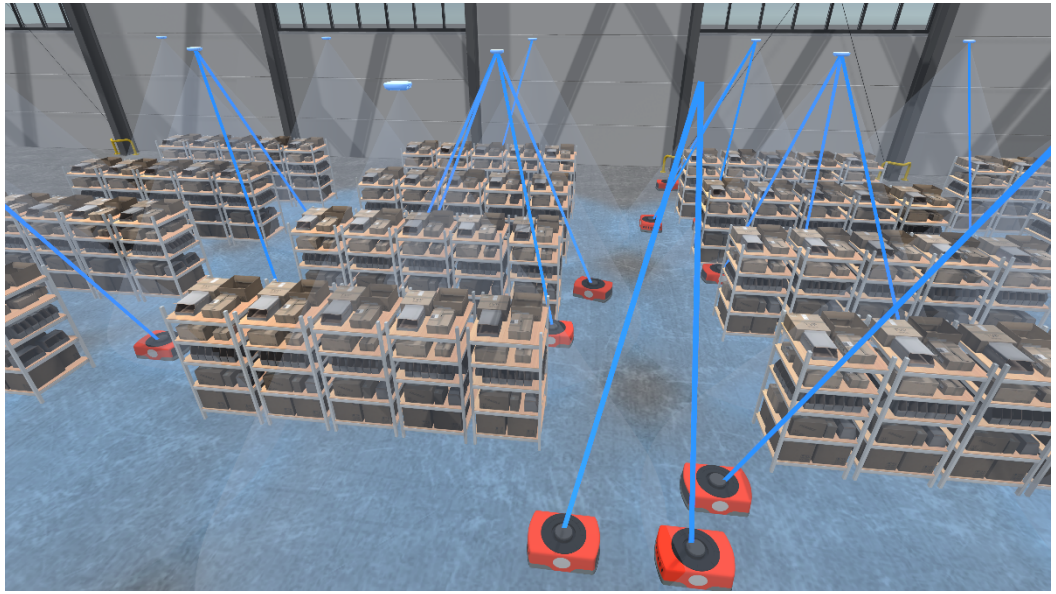
[redacted]

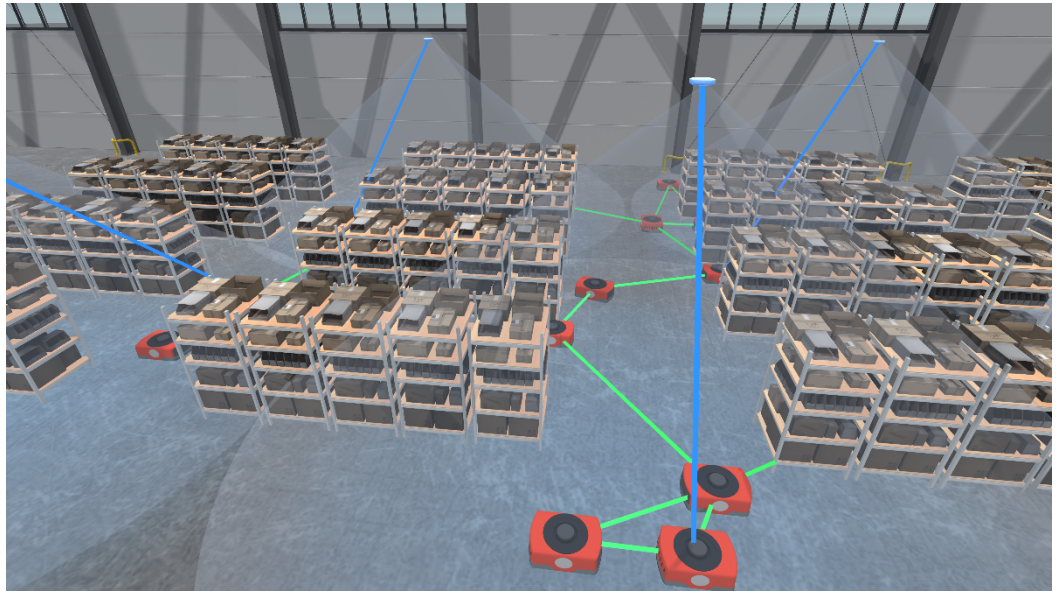
Latency

[redacted]

The 5G Atom concepts: Meshmerize (multi-path) vs. B.A.T.M.A.N. (single-path) demonstrator

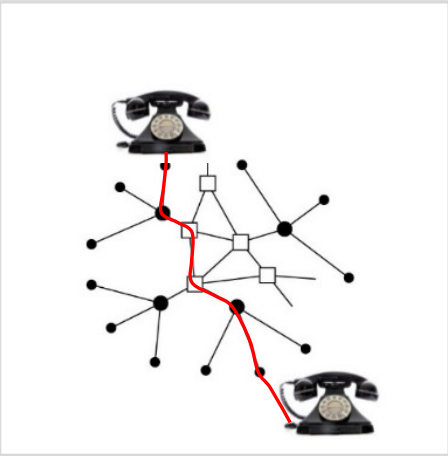
The 5G atom concepts: Combination of multi-path and mesh communication system in an Industry 4.0 environment





Communication Networks

***Circuit* Switched Networks**

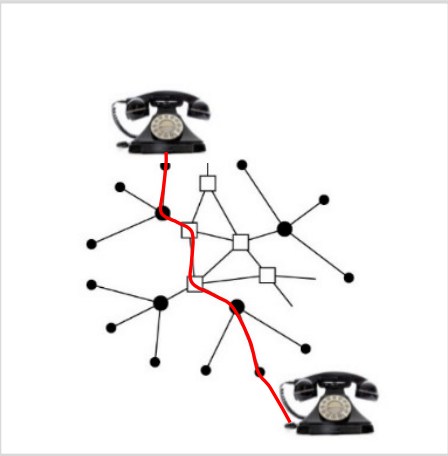


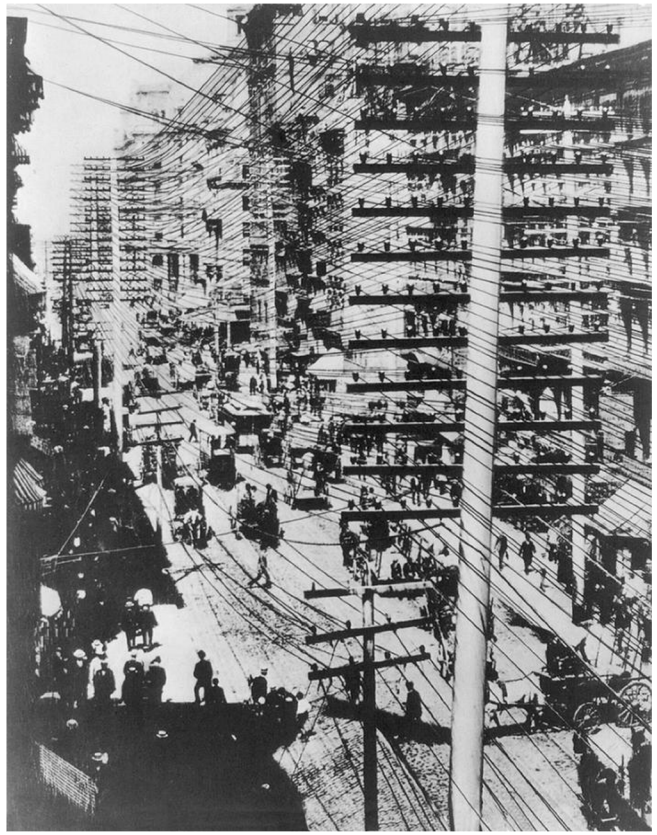
Voice

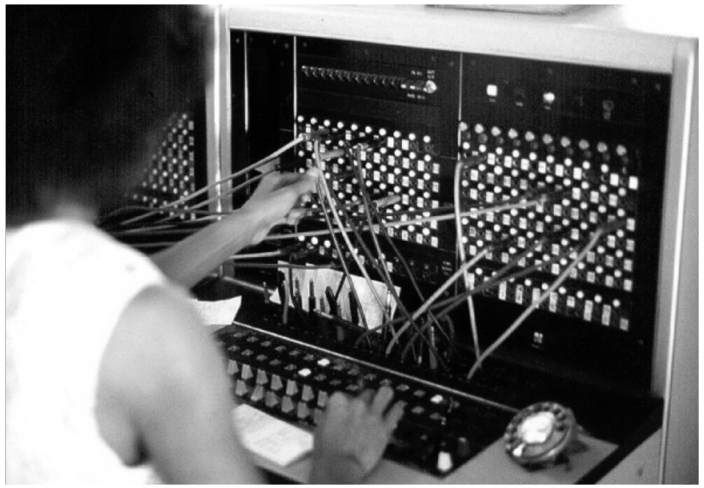
Places

Communication Networks

***Circuit* Switched Networks**



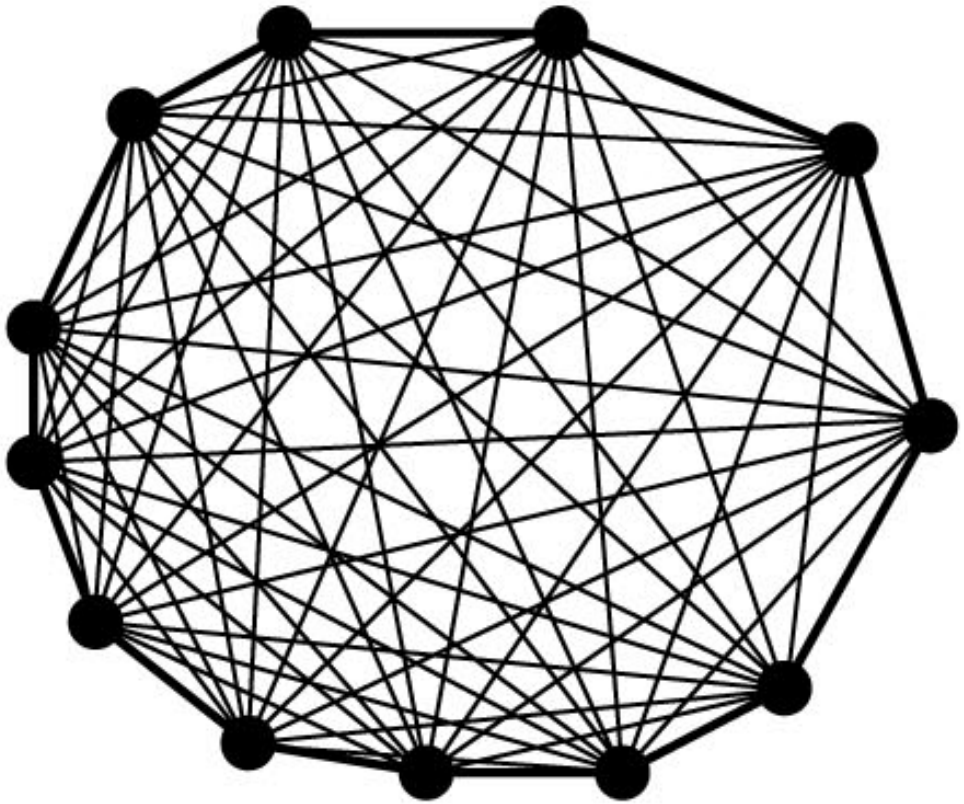


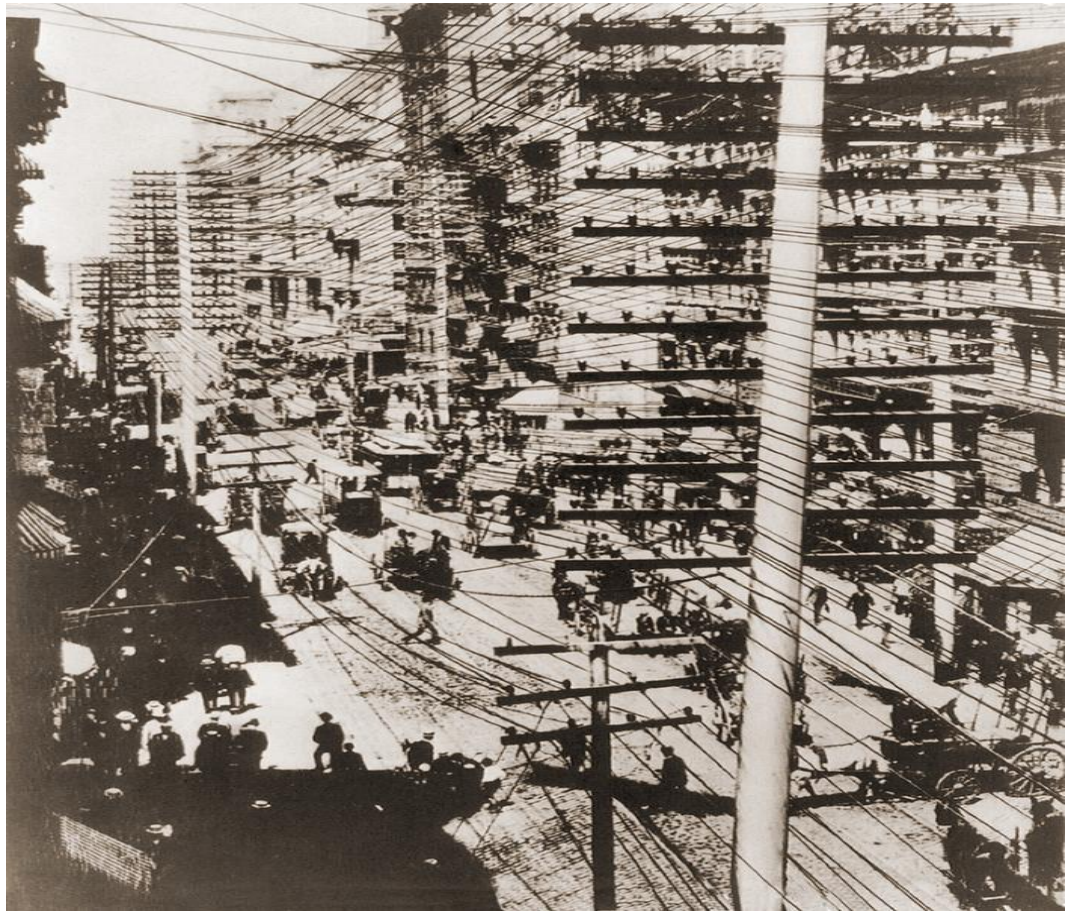


Voice

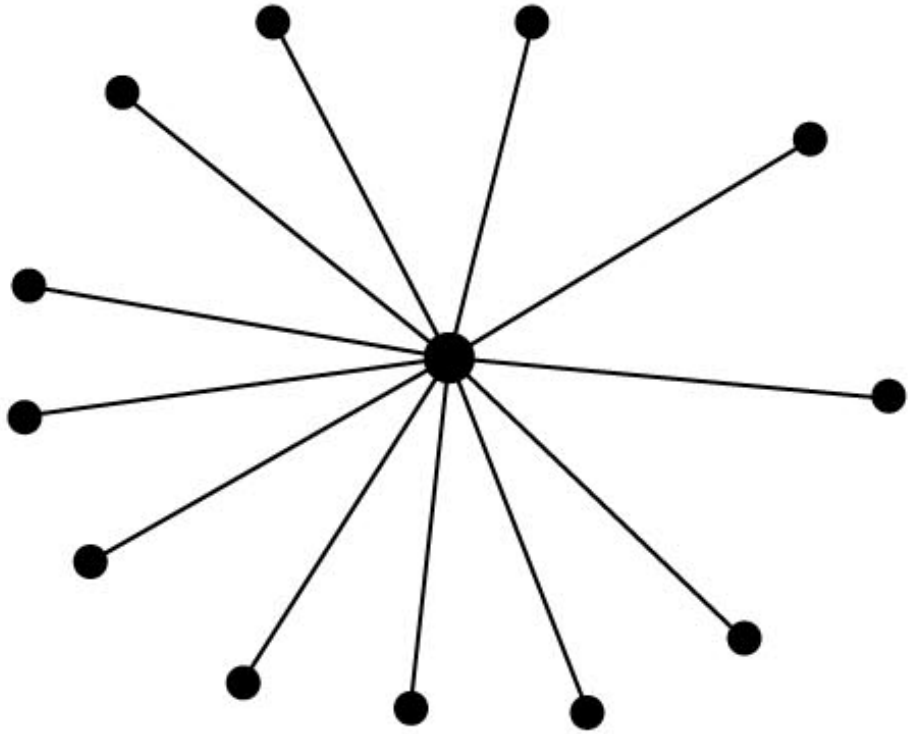
Places

The Telephone System

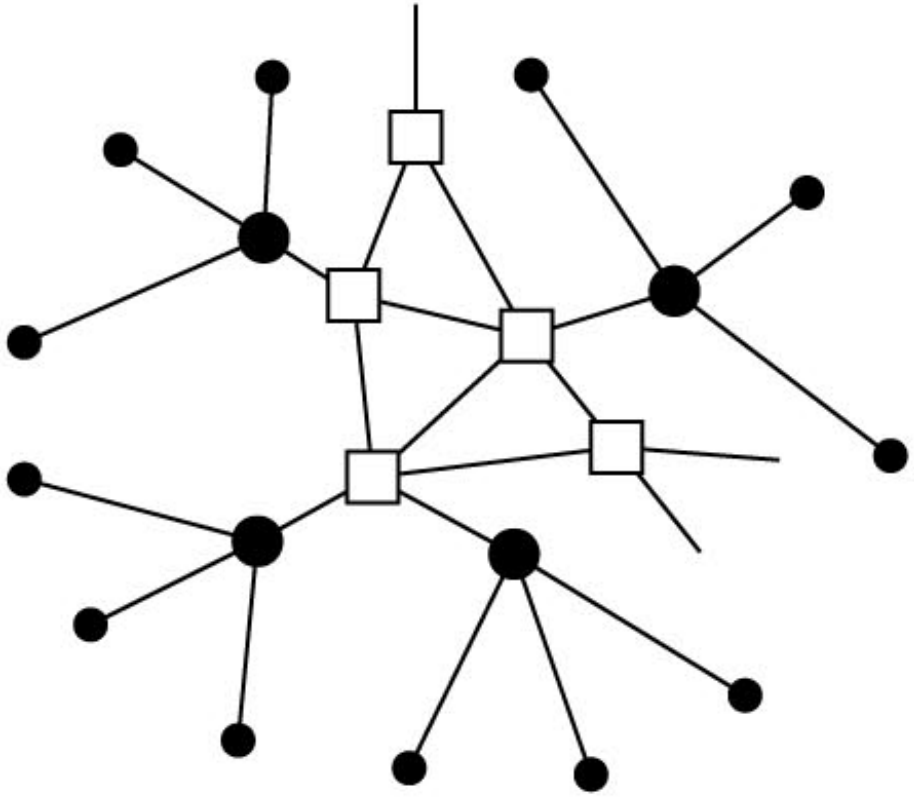


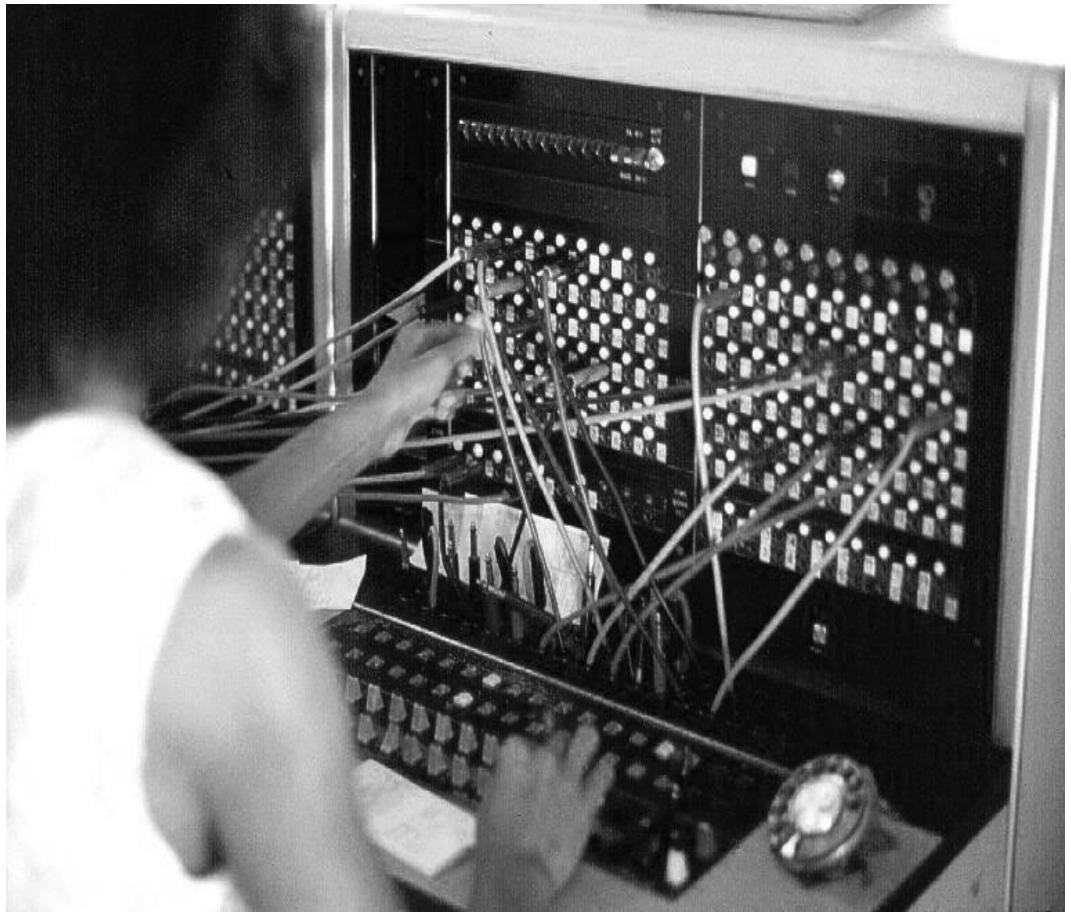


The Telephone System

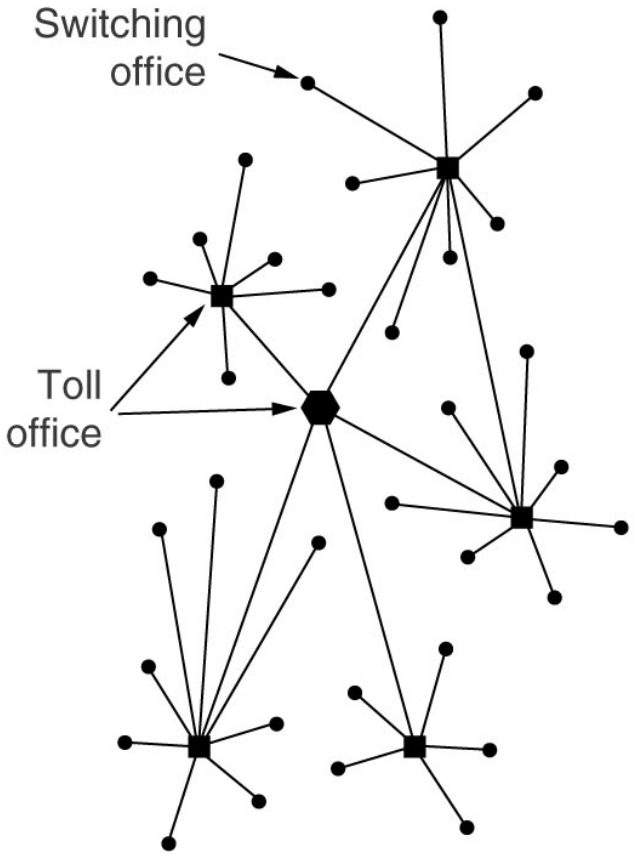


The Telephone System

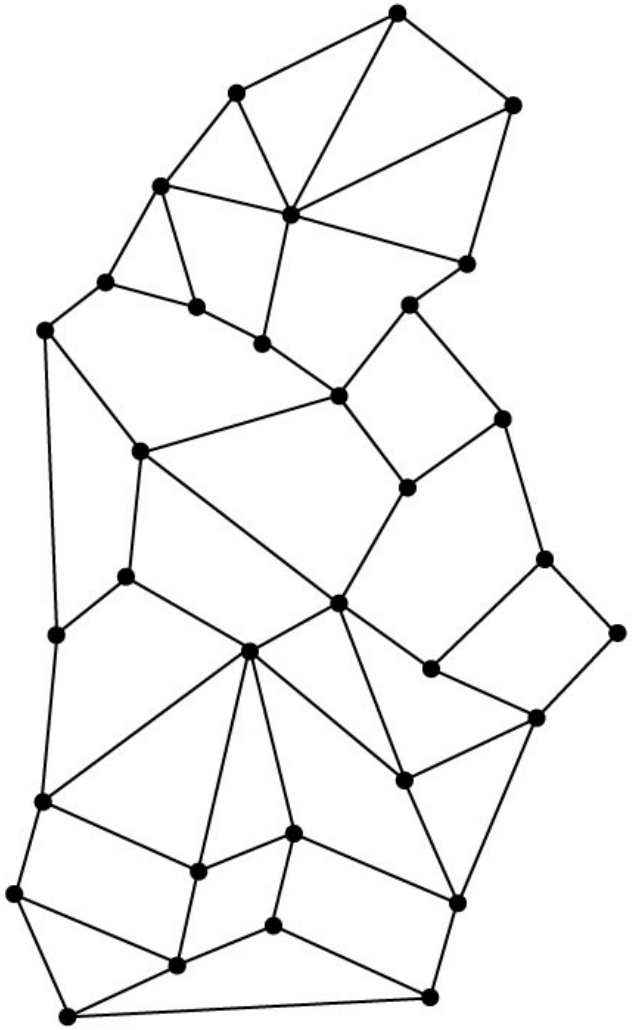




The Internet

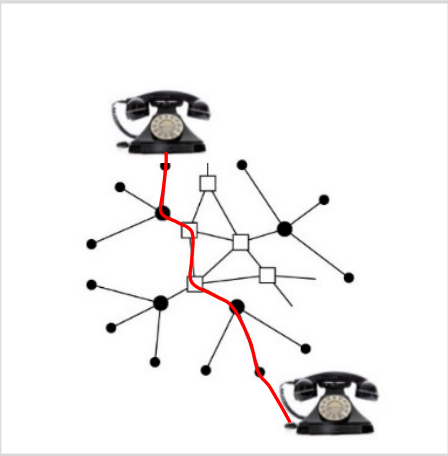


Circuit switched to packet switched



Communication Networks

***Circuit* Switched Networks**



Revolution

***Packet* Switched Networks**

Voice

Places

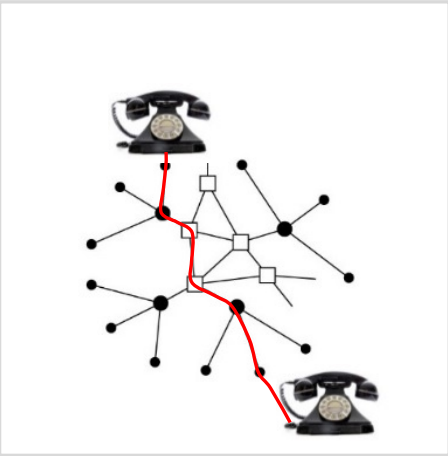
Data

Voice

People

Communication Networks

***Circuit* Switched Networks**



Voice

Places

Revolution

***Packet* Switched Networks**

Data

Voice

People

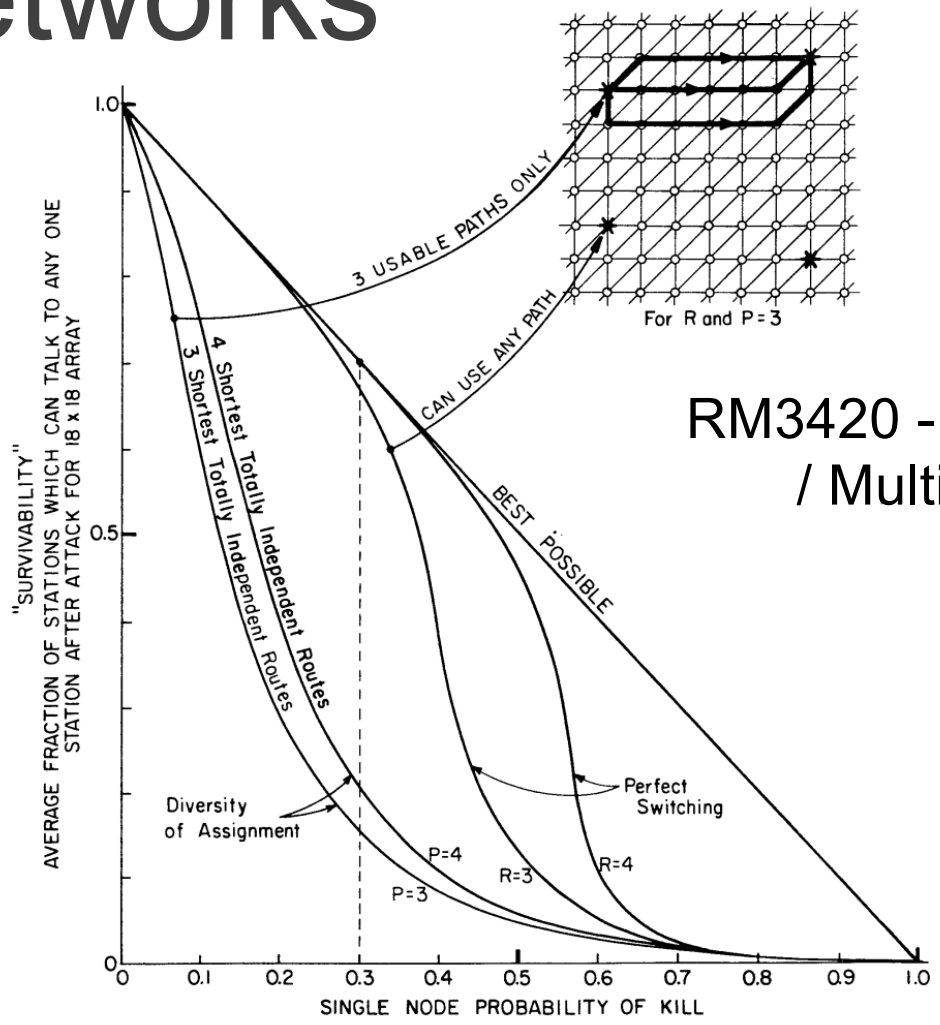
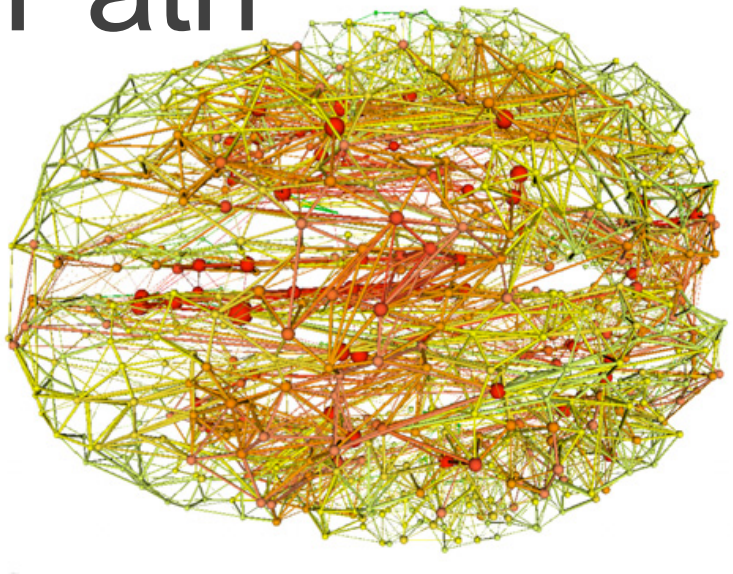


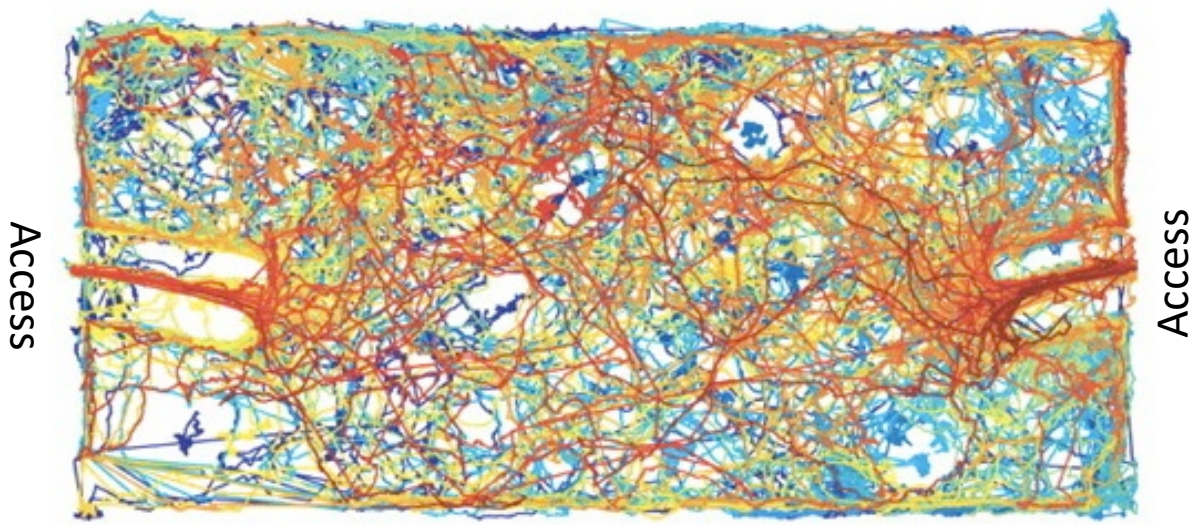
FIG. 8 — Diversity of Assignment vs. Perfect Switching in a Distributed Network.

RM3420 - Diversity / Multipath

Single Path vs. Multi Path

- Comparison with the **brain**
- Our brain uses multiple paths
- Reliability (Pain)





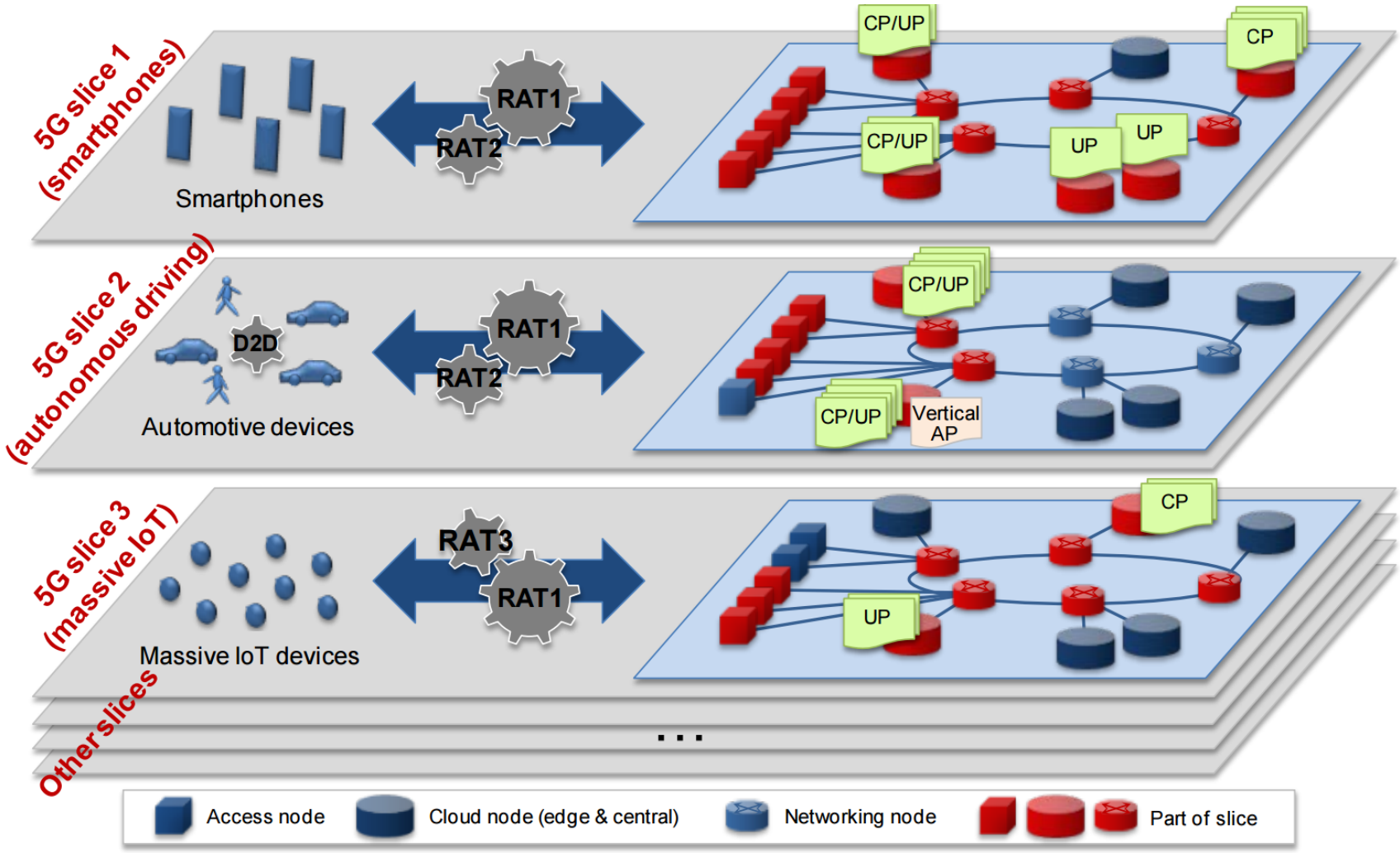
Comparison with **ants**

Food retrieval strategies

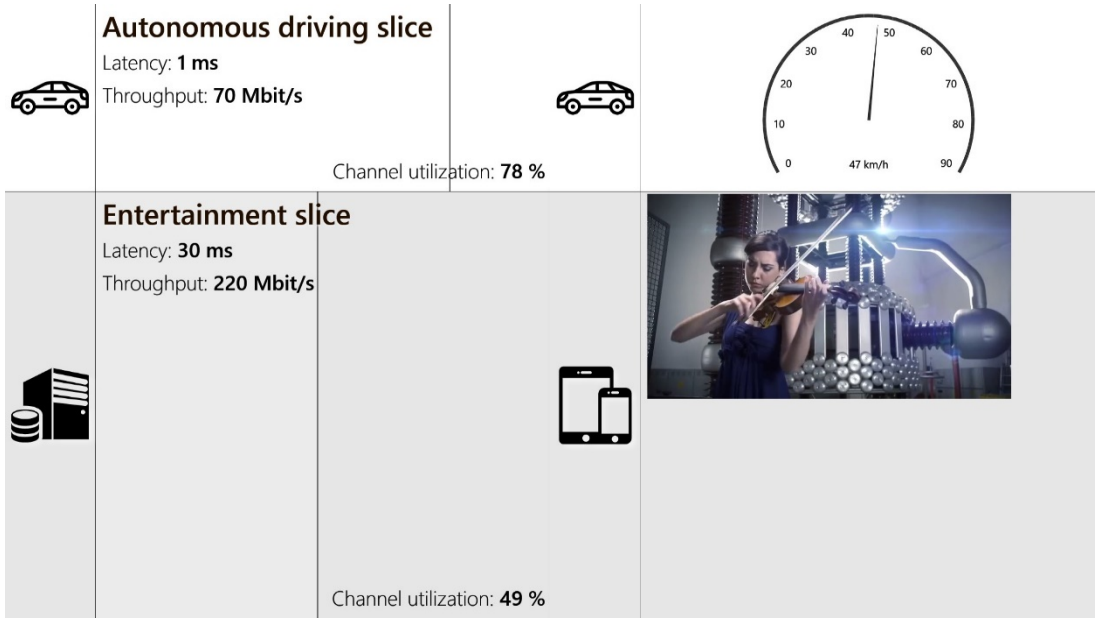
5G Concepts: Mesh

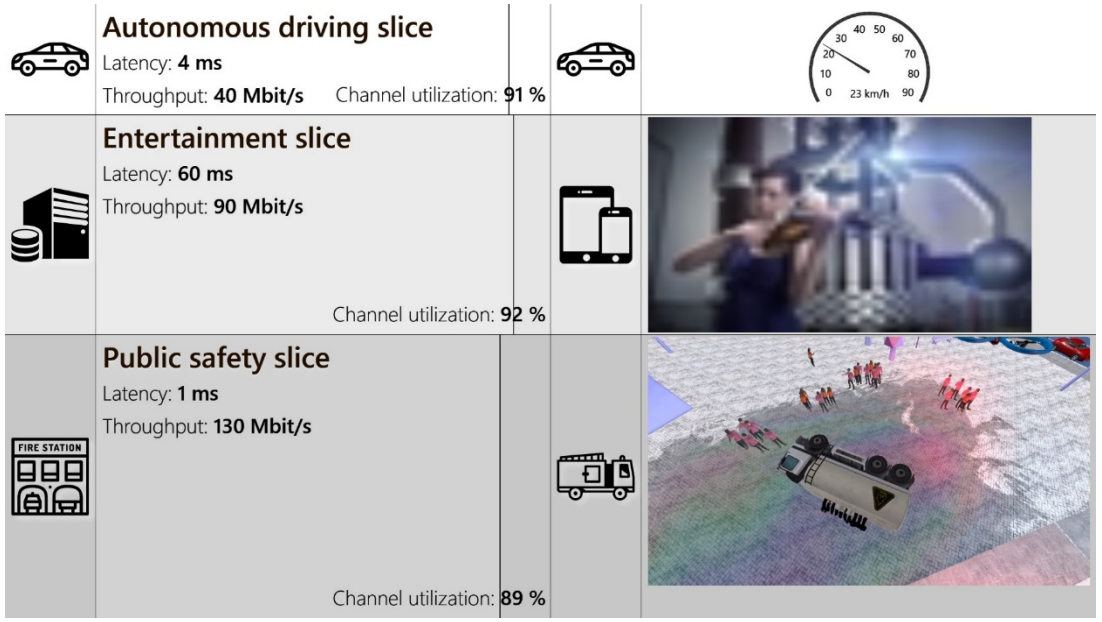
5G Concepts: Network Slicing

Network Slicing



The 5G atom concepts: Network slicing





TECHNISCHE UNIVERSITÄT DRESDEN

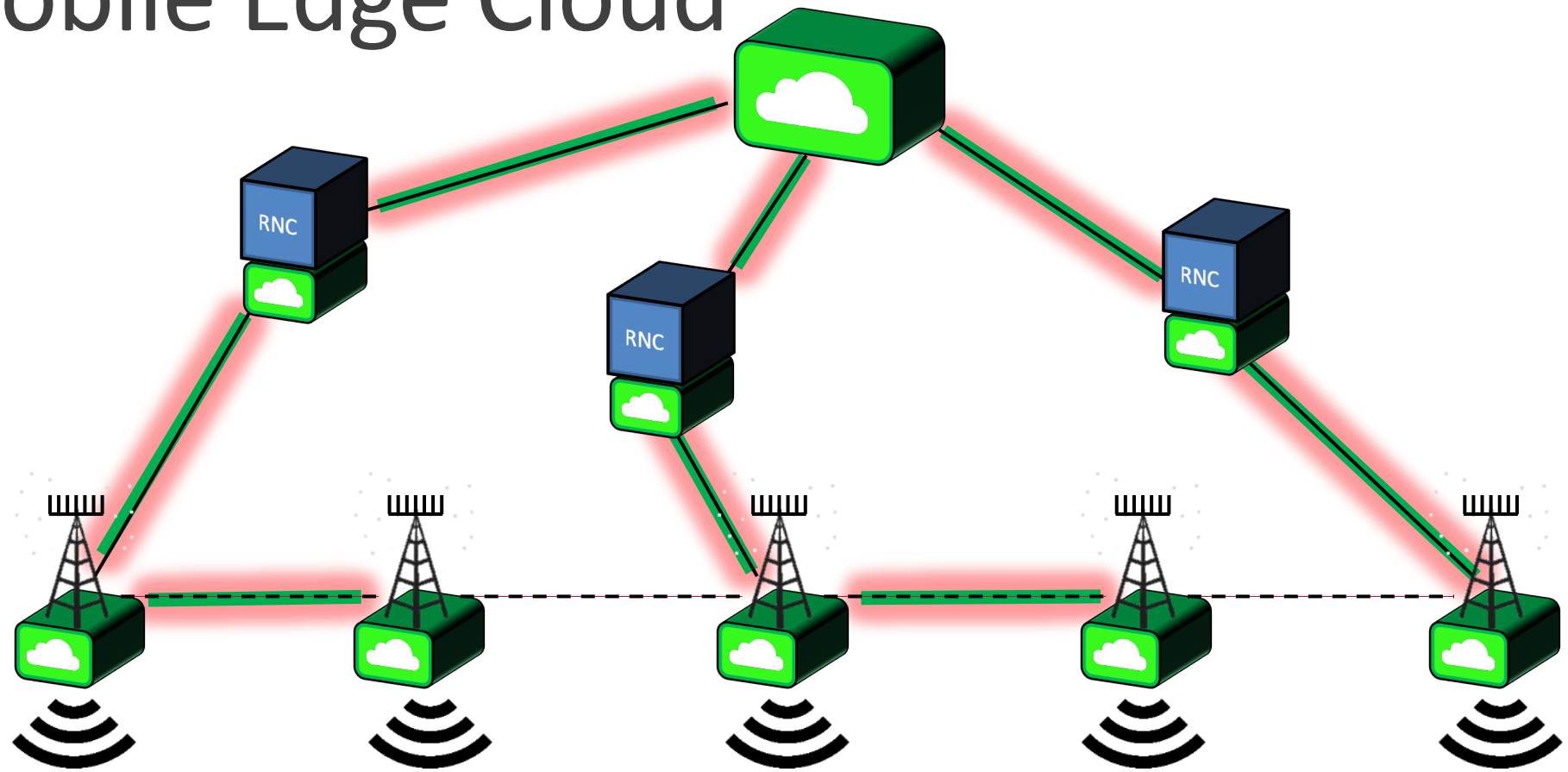
Barcelona Network slicing demo

Made by ComNets
Deutsche Telekom Chair
of Communication Networks

In association with 5G Lab GERMANY

5G Concepts: Mobile Edge Cloud

Mobile Edge Cloud



Mobile Edge Cloud

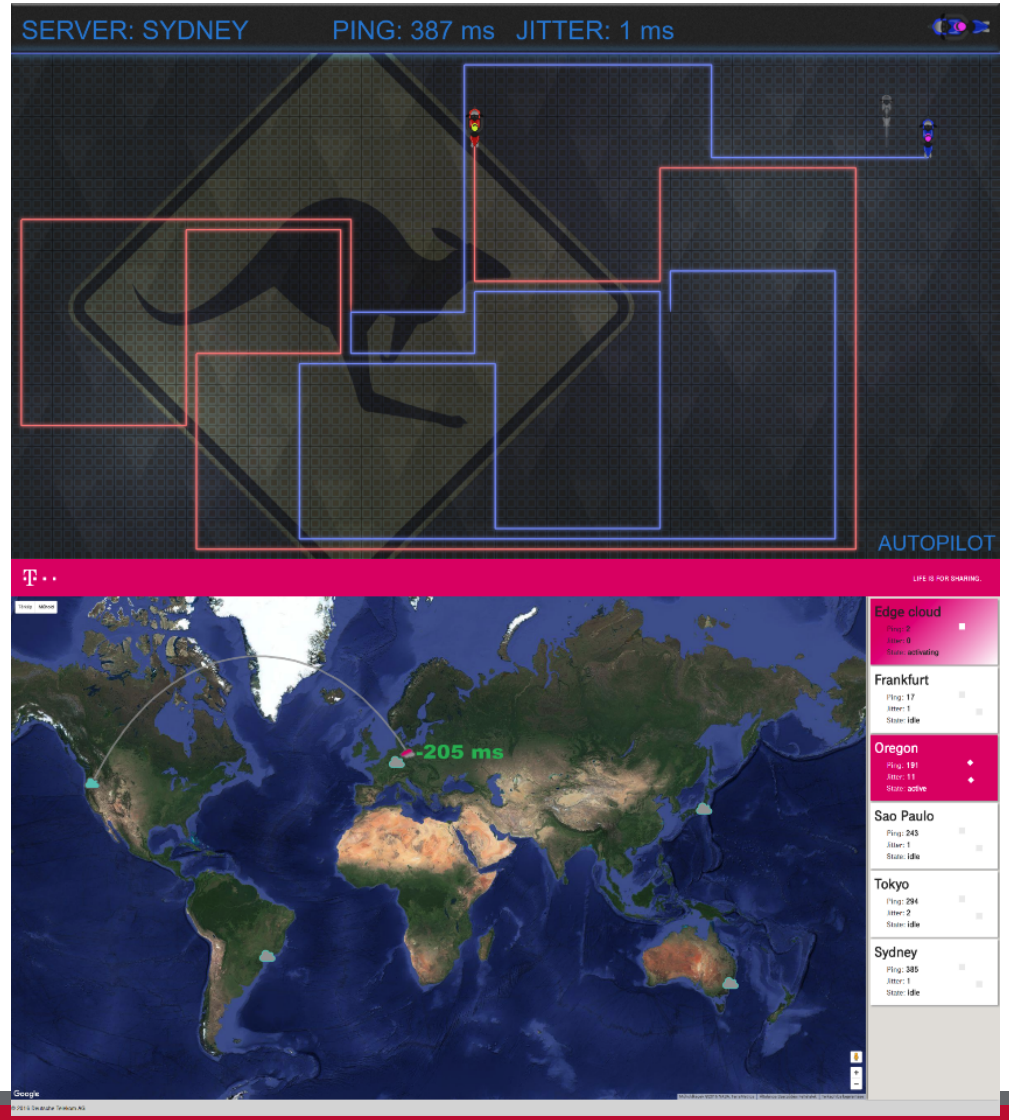
Browser based multiplayer game

Game servers:

- Run in the cloud, as a service
- Latency to the cloud affects the game play (classic gamer's ping problem)

Game can be migrated LIVE between the different cloud servers.

Thus game always can run on the closest edge cloud server.



Mobile Edge Cloud Demo

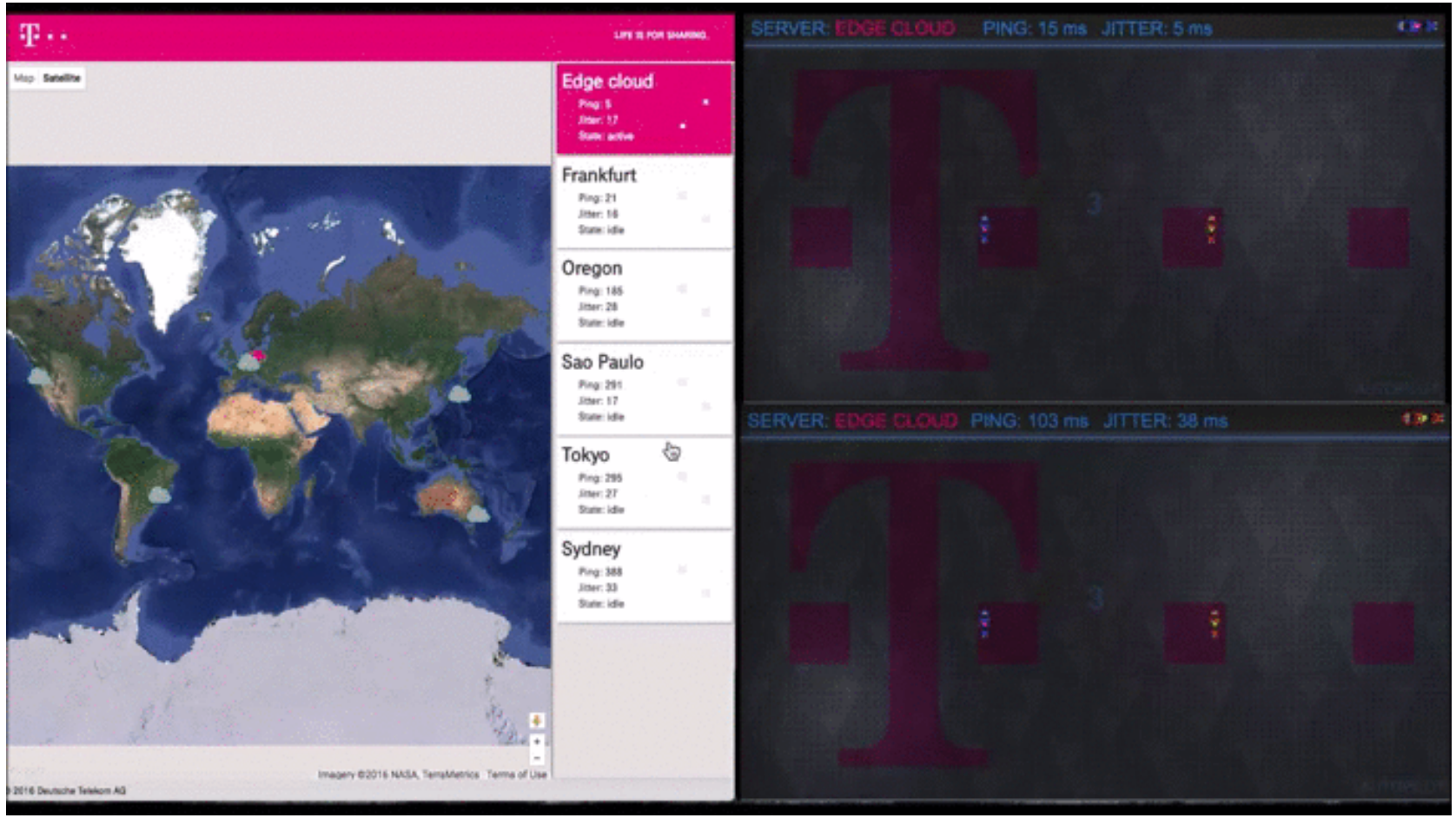
Five cloud servers: Oregon (US), Frankfurt, Sao Paulo, Tokyo, Sydney

One edge cloud

Soft handover – Zero downtime.

‘Ghost’ bots to show latency effect

Display latency, Jitter to each server.



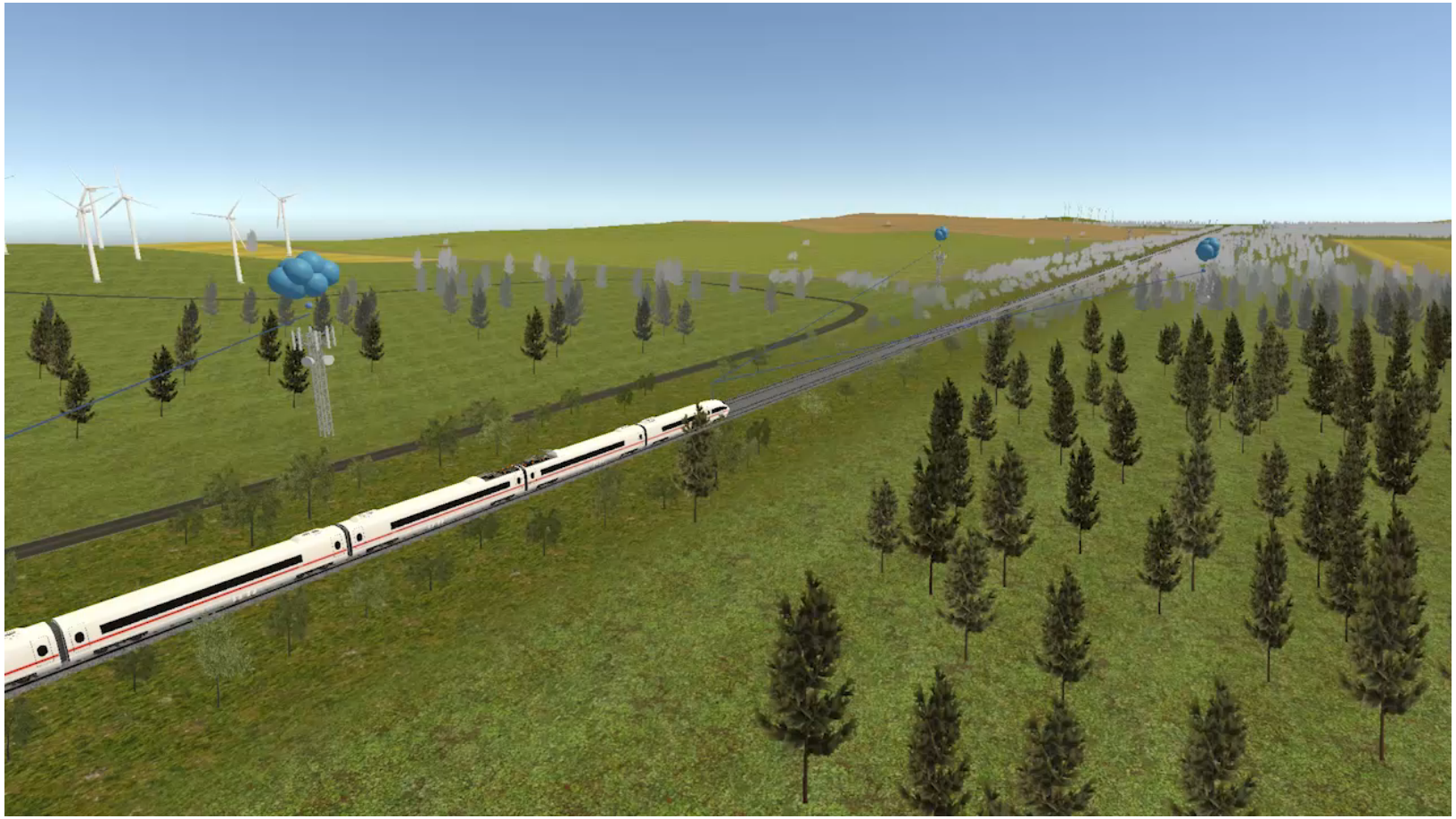
JITTER: 3.11 MS
LATENCY: 82 MS

TECHNISCHE UNIVERSITÄT DRESDEN

BMW MEC demo

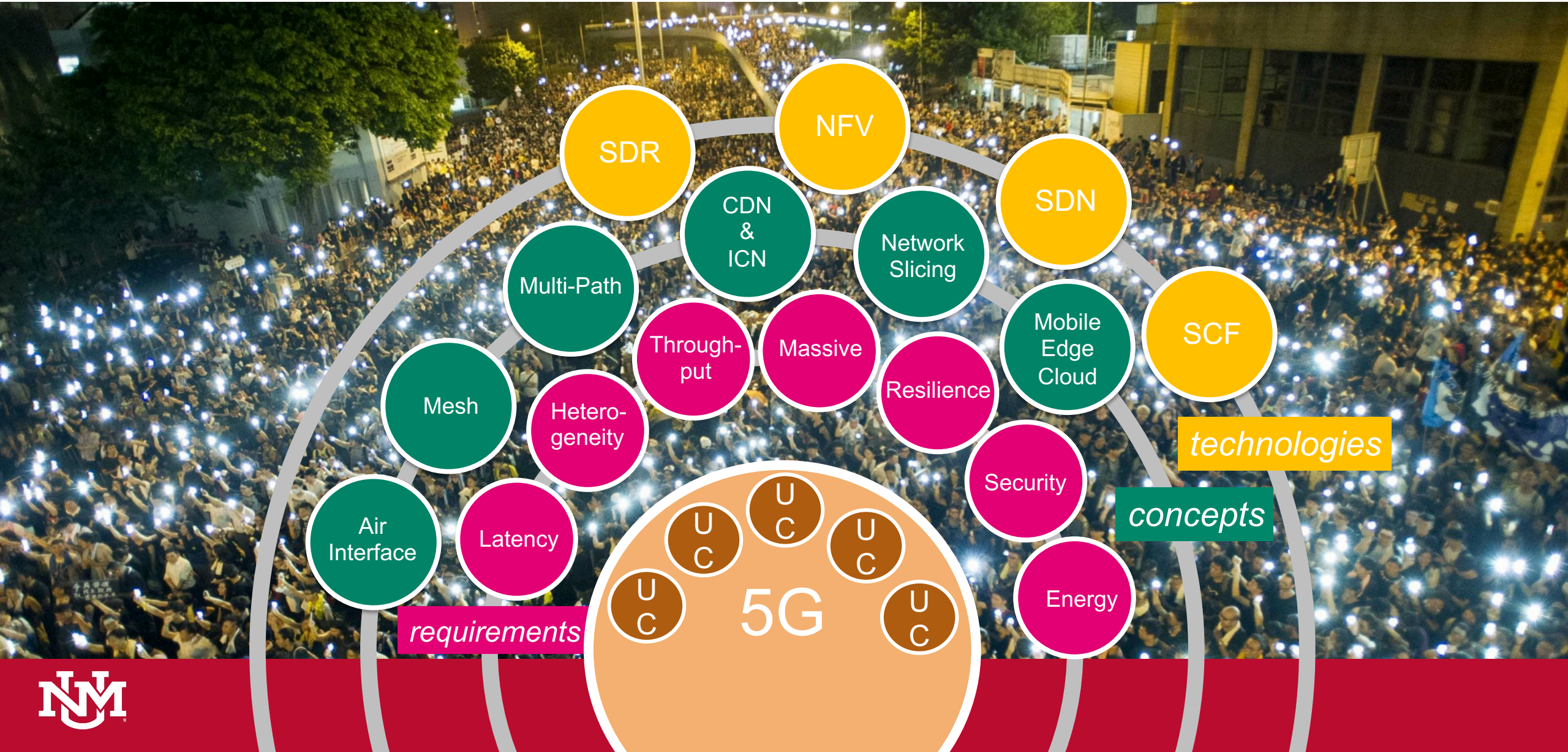
Made by ComNets
Deutsche Telekom Chair of Communication Networks

In association with 5G Lab GERMANY



5G technologies
the software belt

5G atom definition



Software Defined Radio

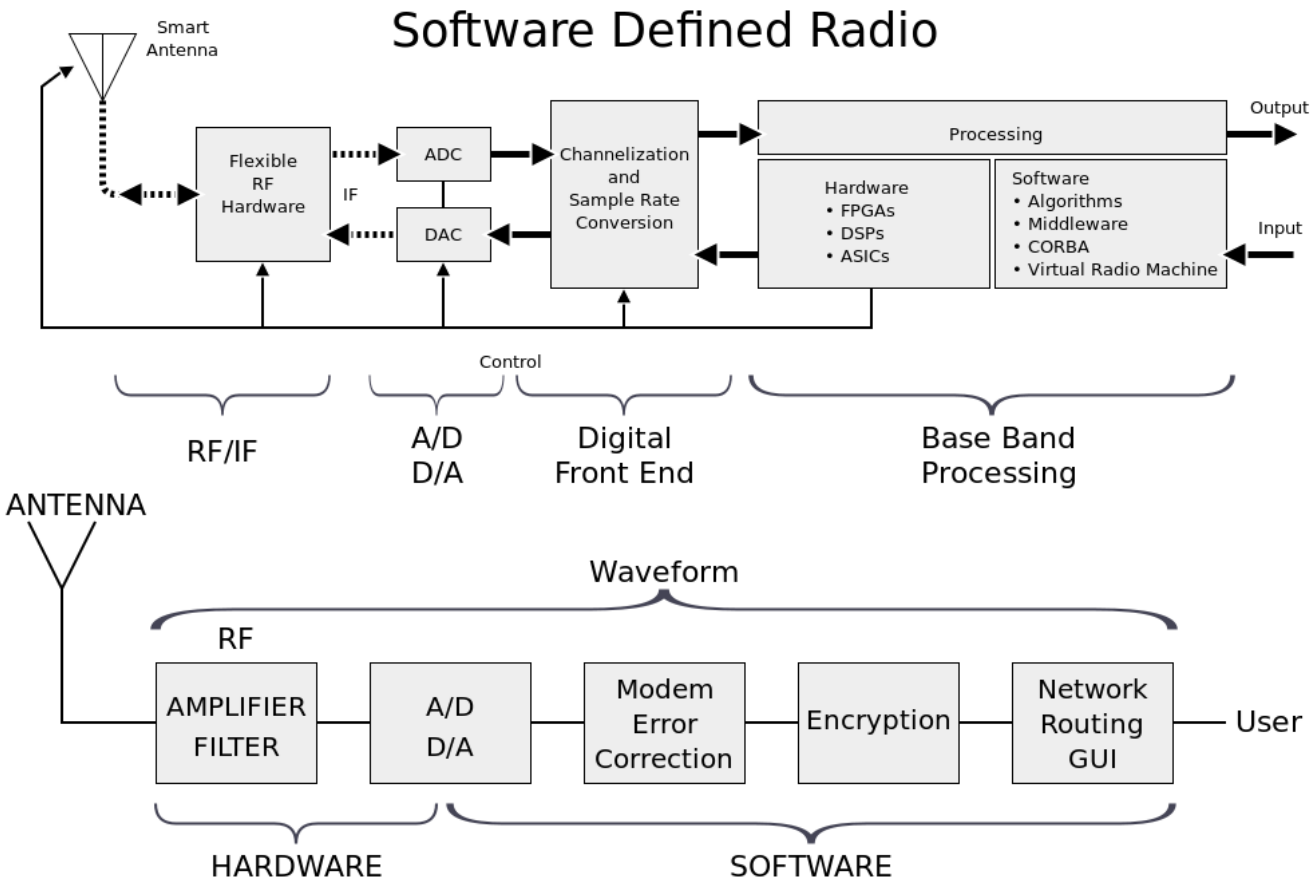
Software Defined Radio

Different concepts

- Reuse of hardware components
- Flexible control of components

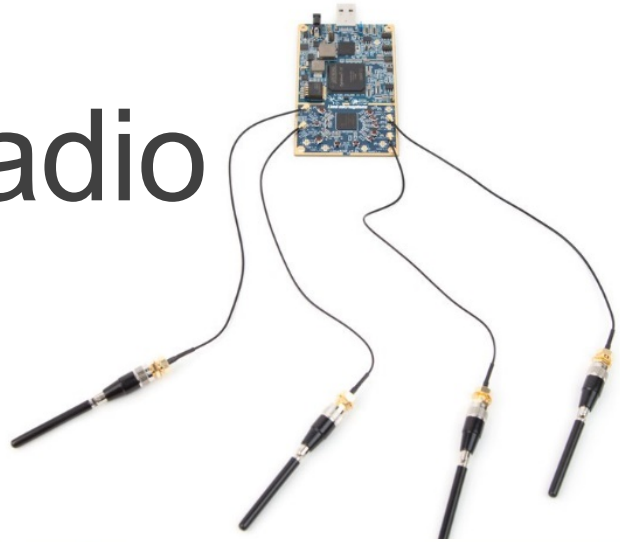
Softwareization of the air interface

End to End paradigm



Software Defined Radio

GNUradio



New kid on the block LimeSDR

Current activites at the chair

Interesting

- Low latency
- Network coding at the edge
- Analog network coding
- Multi connectivity

Software Defined Networks & Network Function Virtualization

Motivation for SDN and NFV

SDN was motivated by the relation of ***computation*** and ***communication***, which led to new principles for ***software*** and ***networking***.

communication

computation

computation and ***communication***

Motivation for SDN and NFV

SDN was motivated by the relation of ***computation*** and ***communication***, which led to new principles for ***software*** and ***networking***.

NFV was motivated by the flexibility, timely deployment and financial gains of ***cloud and OTT providers***, which was not available to ***network operators.***

SDN and NFV are often intertwined

SDN & NFV

Software Defined Networks

SDN advocates to replace distributed static network protocols with centralized flexible software applications.

- Enables fast experiments with new ideas
- Fast deployment of software compared to long lasting standardization processes
- Optimization due to centralized control as a function of time
- New functionality can be deployed in nearly no time relocated, and upgradet depending on the needs.

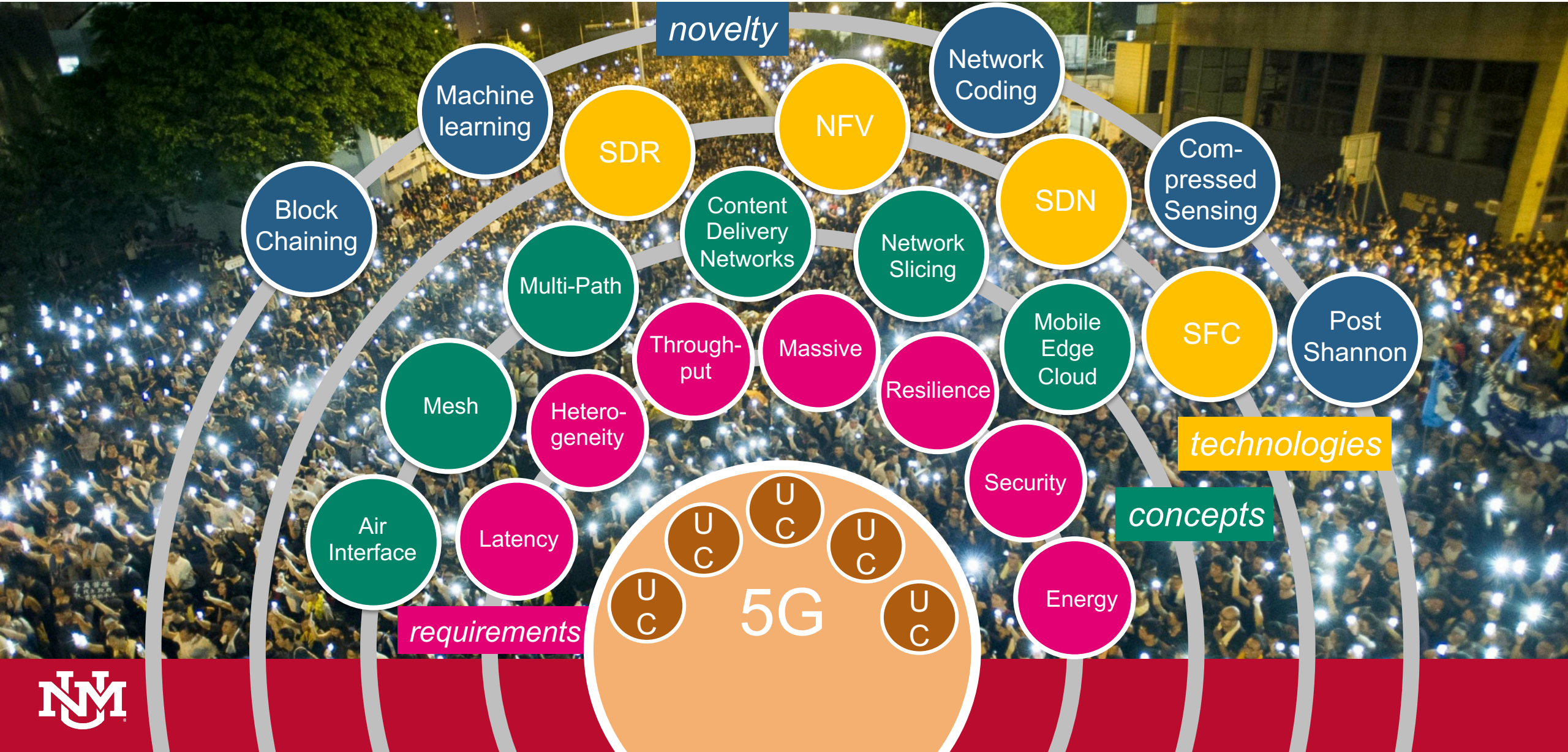
Network Function Virtualization (NFV)

NFV advocates to use generic hardware running software solution compared specialized hardware.

- Hardware becomes cheaper (COTS)
- Relocation of functionality to optimize network performance such as latency, capacity, etc.
- New functionality can be deployed in nearly no time relocated, and upgradet depending on the needs.

5G novelty

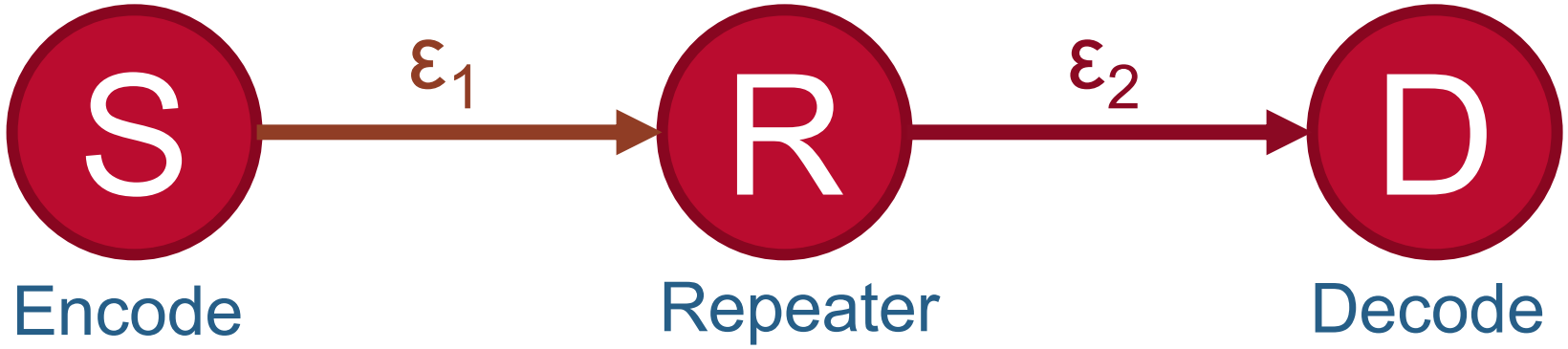
5G atom definition



5G Network Coding

https://www.youtube.com/playlist?list=PLtngEjKSkXc04VBKxJR-ZNFKhyxW2Uny2

Network Coding

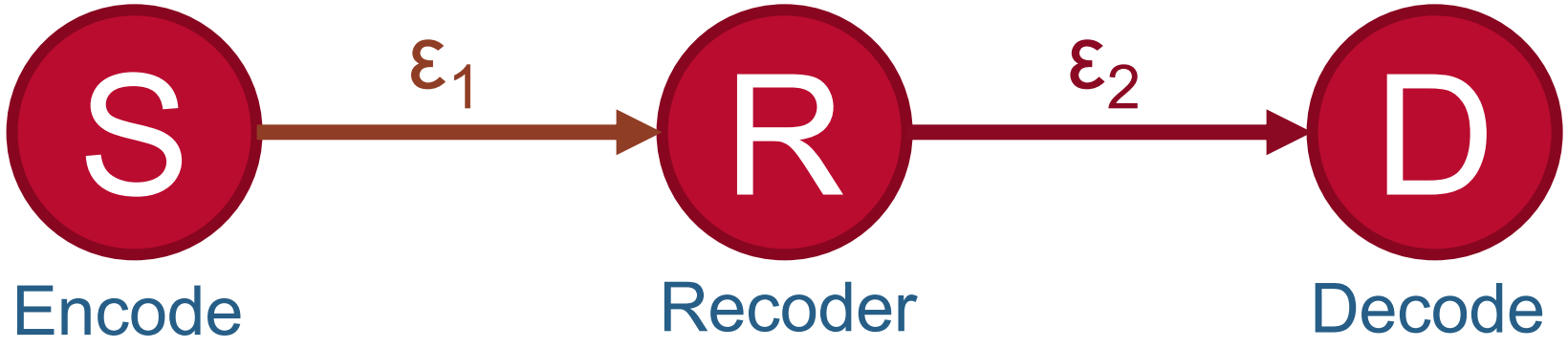


Reed Solomon
LDPC
LT
Raptor

$(1-\varepsilon_1)(1-\varepsilon_2)$

Store and Forward

Network Coding



Reed Solomon
LDPC
LT
Raptor

$(1-\varepsilon_1)(1-\varepsilon_2)$

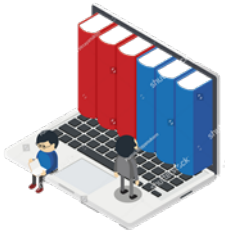
Store and Forward

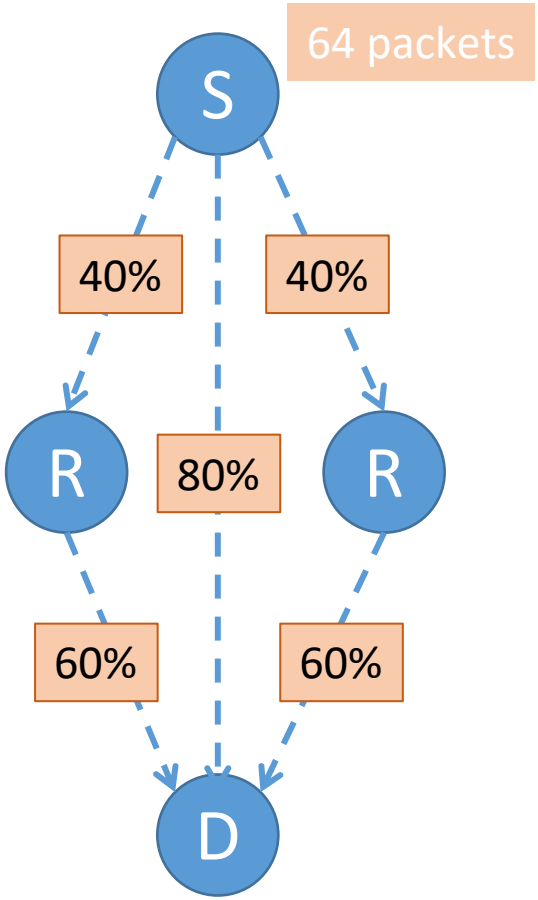
Network Coding

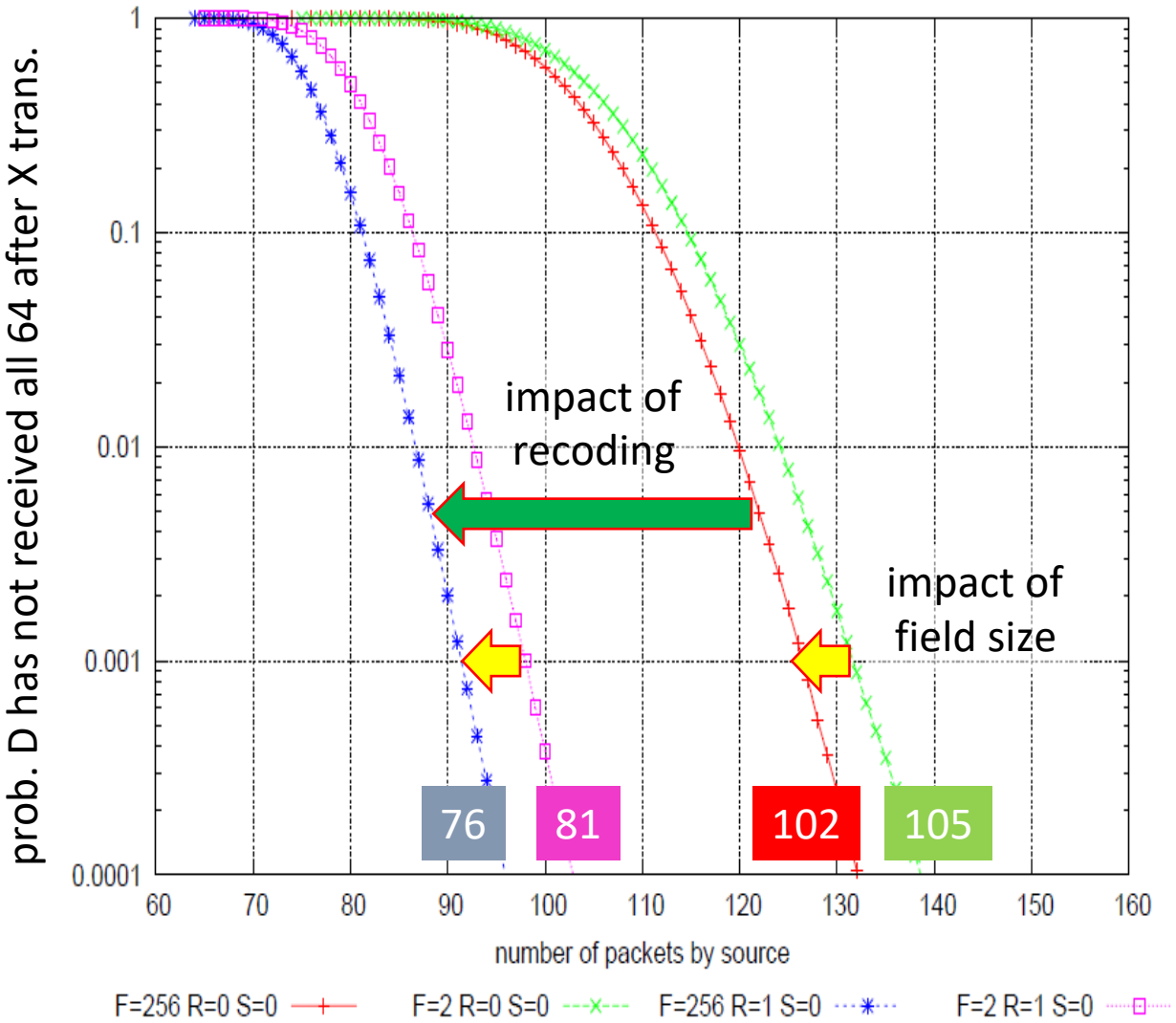
$\min\{(1-\varepsilon_1);(1-\varepsilon_2)\}$

Compute and Forward

Impact of Recoding







No need for signalling!

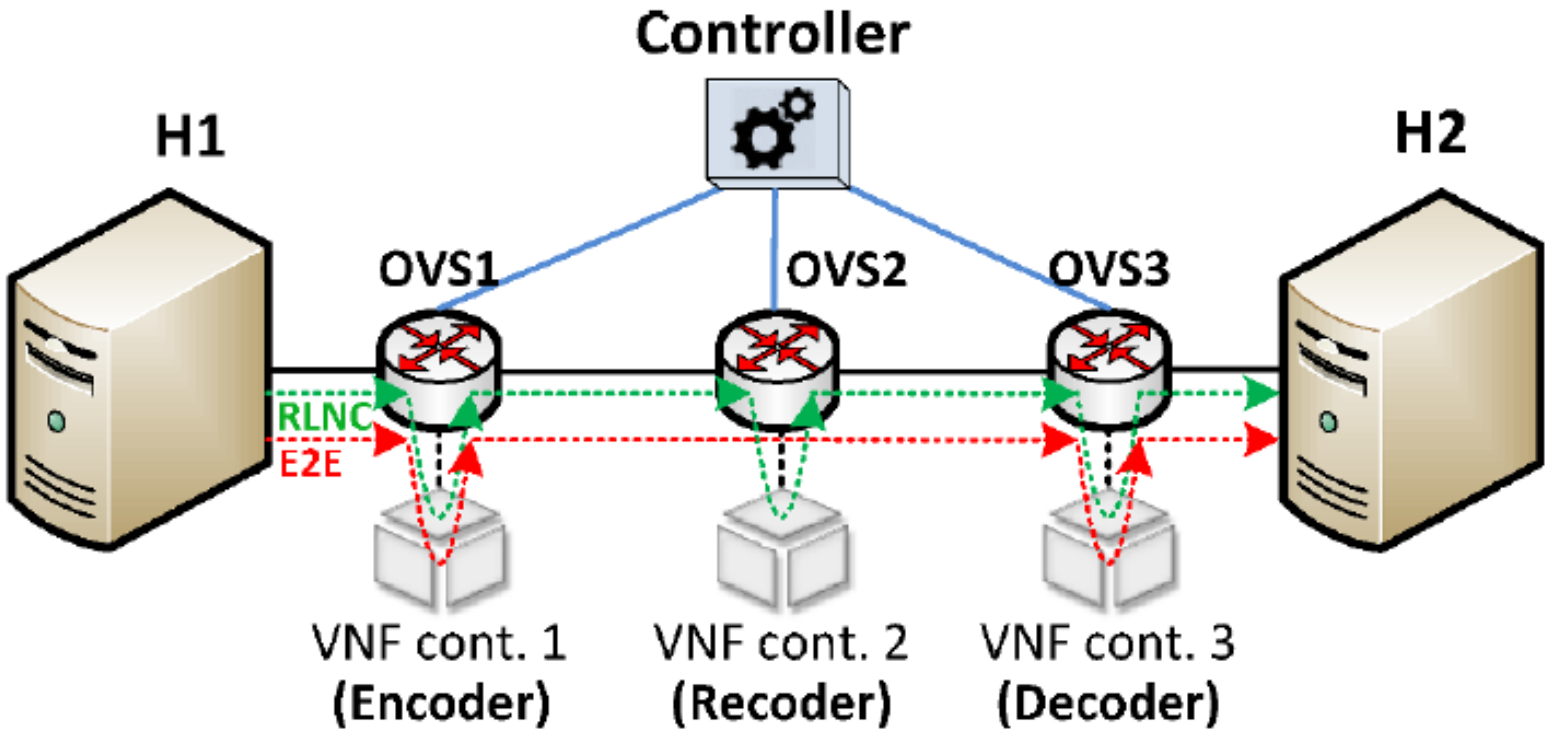
Sliding Window

Encoder	Content	Decoder

SlidingWindowEncoderFactoryBinary
~~SlidingWindowEncoderFactoryBinary16~~
SlidingWindowEncoderFactoryBinary4
SlidingWindowEncoderFactoryBinary8

SDN testbed & Network Coding

Example with ESCAPE prototyping environment



5G Compressed Sensing

Compressed Sensing and Network Coding Characteristics

Compressed Sensing

- Linear superposition
- Random (sampling)
- Source aware
- Sparsity
- Under-determined
- Optimization problem

$$y^{m\times 1} = A^{m\times n}x^{n\times 1}, m \ll n$$

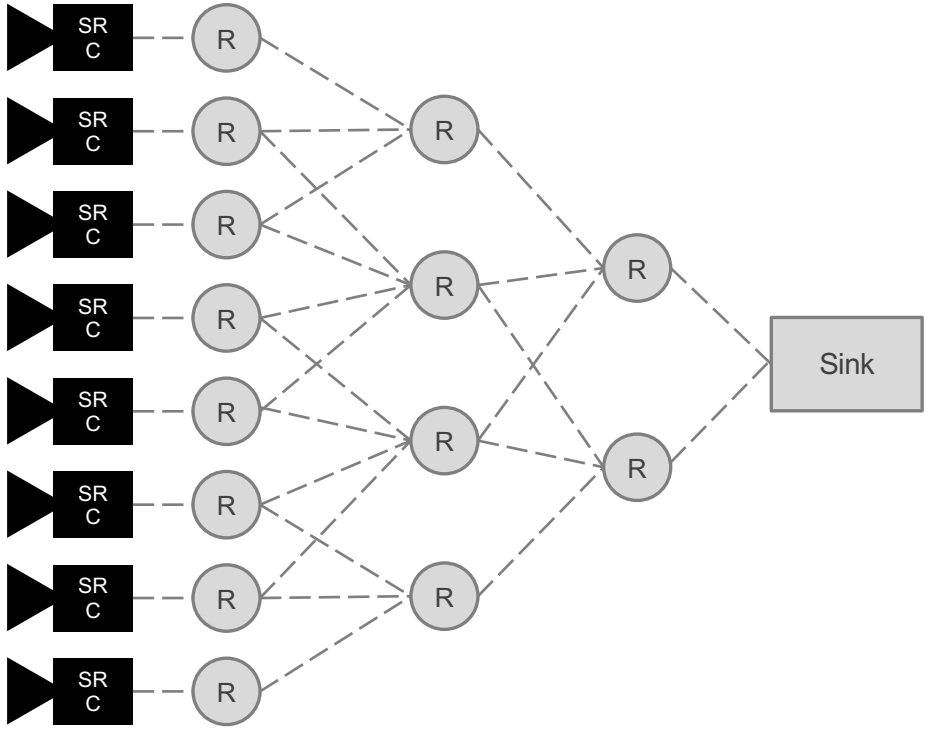
Network Coding

- Linear superposition
- Random (coefficients)
- Source agnostic
- Over-determined (full rank)
- Linear system of equations

$$y^{(n+r)\times 1} = A^{(n+r)\times n}x^{n\times 1}, r \geqslant 0$$

Combine NC and CS

- Objective: Combine CS and NC (analog and digital) in theory and implementation to improve delay ↓, resilience ↑ and complexity ↓.
- Agnostic combination CS/NC: Only individual gain per camera (spatial correlation not exploited), reconstruction/decoding at the sink resulting in high complexity
- Proposed joint CS/NC design (analog and digital): Holistic in-network processing based on compressed compute and forward (CCF) with distributed partial decoding and clever protocol design (active sensing).



Motivation – Pure Network Coding in GF2 (2009)

(a)

$$\begin{pmatrix} \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} & \alpha_{1,4} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} & \alpha_{2,4} \\ & & & \end{pmatrix}$$

(b)

$$\begin{pmatrix} \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} & \alpha_{1,4} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} & \alpha_{2,4} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} & \alpha_{3,4} \\ & & & \end{pmatrix}$$

(c)

$$\begin{pmatrix} \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} & \alpha_{1,4} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} & \alpha_{2,4} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} & \alpha_{3,4} \\ \alpha_{4,1} & \alpha_{4,2} & \alpha_{4,3} & \alpha_{4,4} \end{pmatrix}$$

Sparsity in the field size!

MV Pedersen, J Heide, FHP Fitzek, T Larsen; PictureViewer-a mobile application using network coding; European Wireless Conference, 2009; EW 2009; pages 151-156.

Motivation – Pure Network Coding in GF2

Received Coded Packets

Decoding Matrix

[redacted]

Motivation – Network Coding in GF2 with Sorting

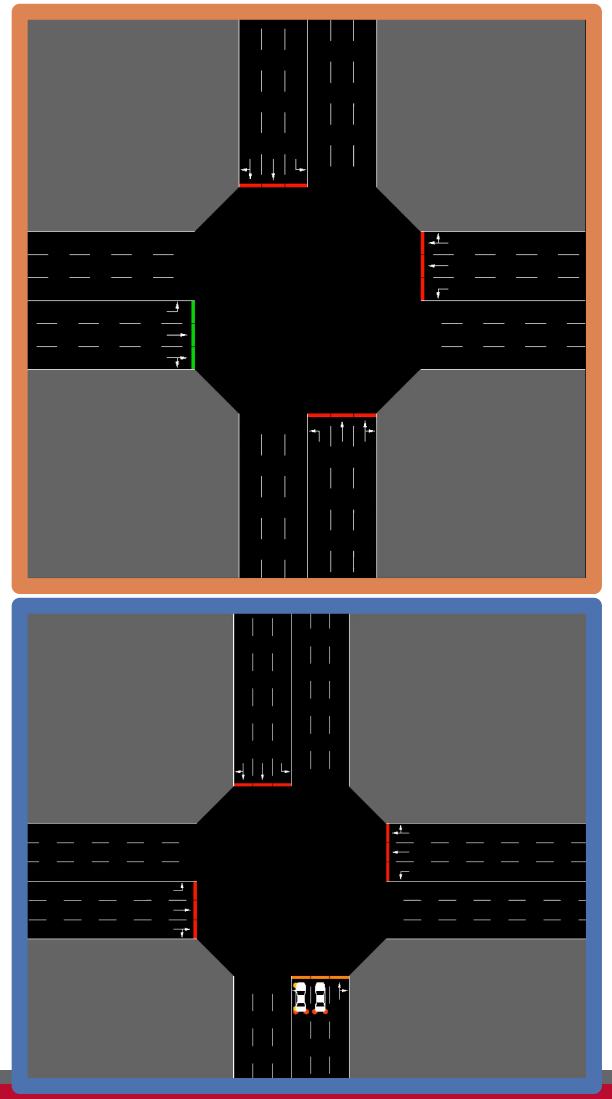
Received Coded Packets

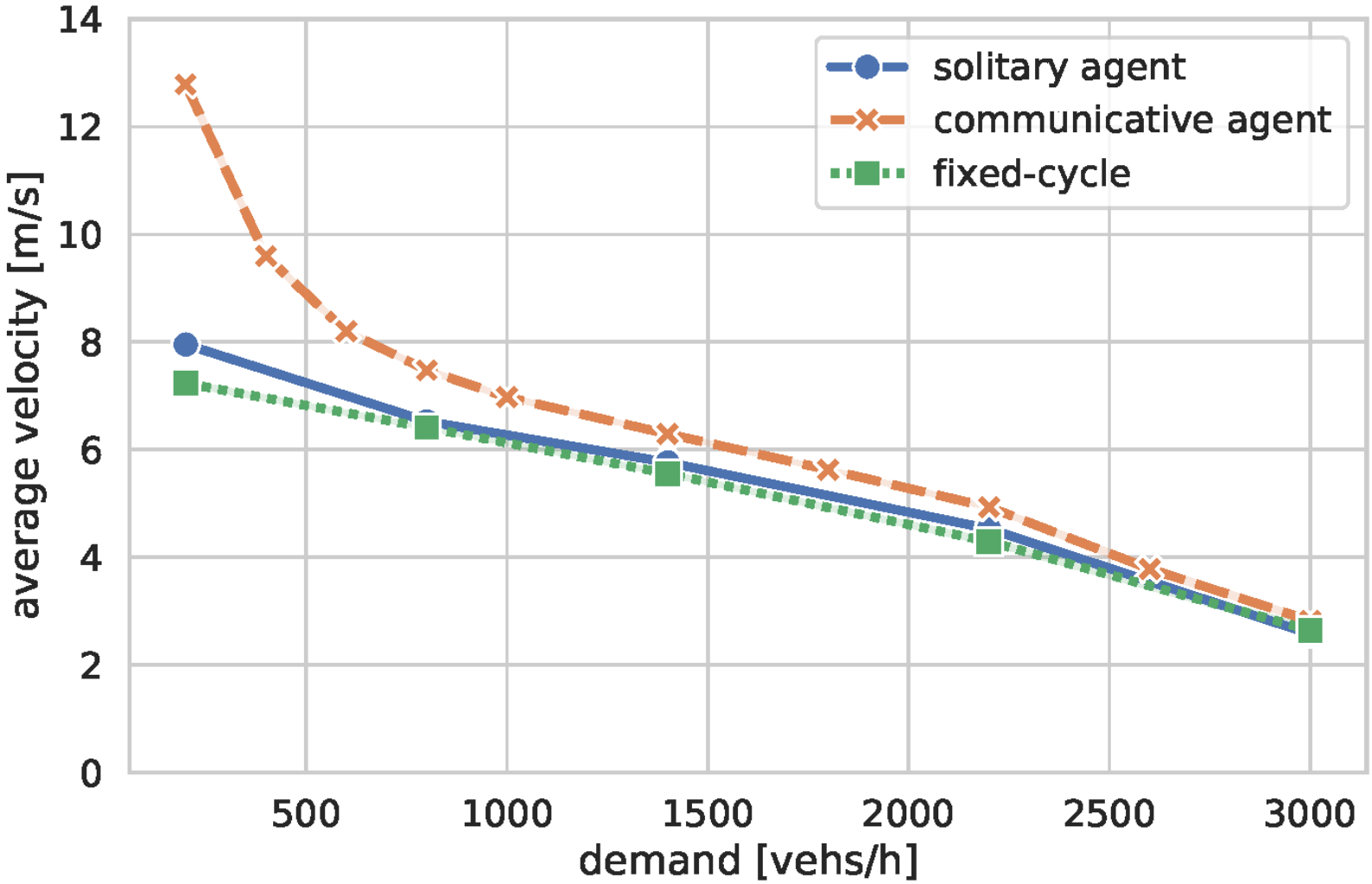
Decoding Matrix

[redacted]

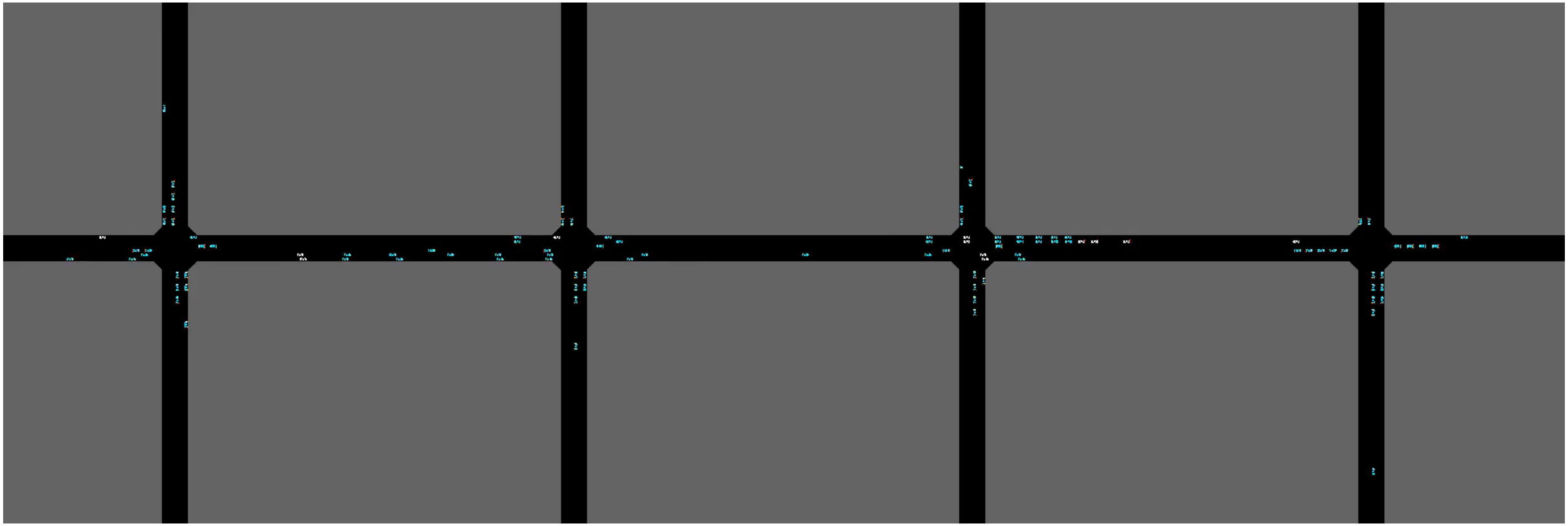
AI (just machine learning)

Communication and AI



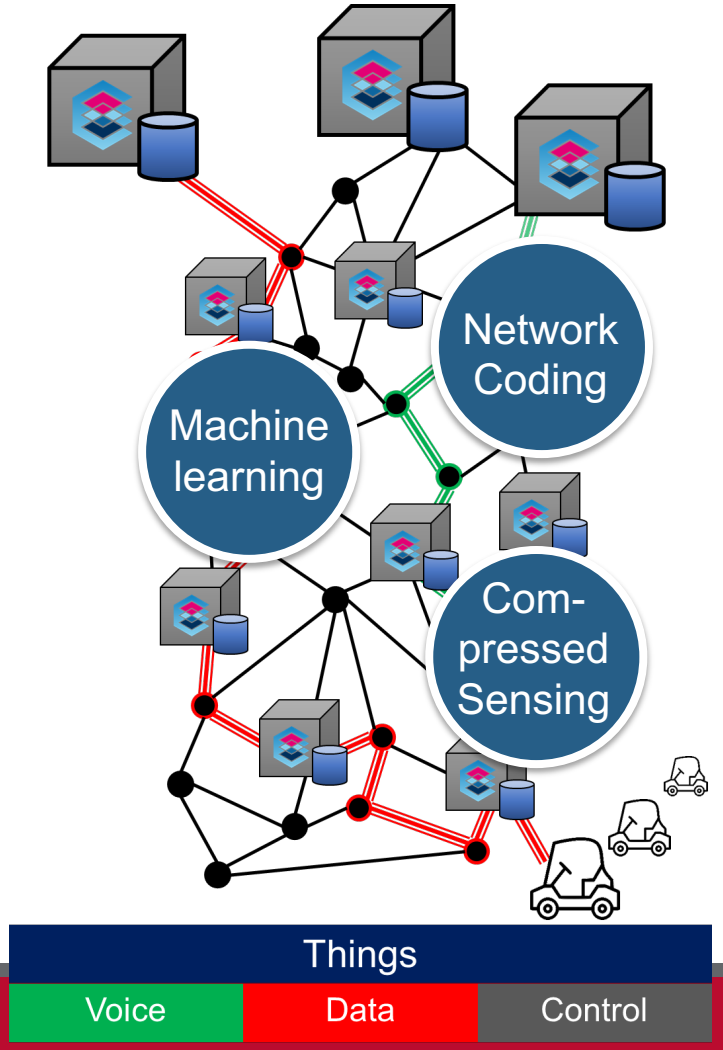


AI: Learned Multi-Intersection Management



Remember the Need of Computing in Communication Networks

- It really happens in the network!



Mapping it back to the book

Computing in Communication Networks

PART 1 FUTURE COMMUNICATION NETWORKS AND SYSTEMS

PART 2 CONCEPTS

PART 3 ENABLING TECHNOLOGIES

PART 4 INNOVATION TRACK

PART 5 BUILDING THE TESTBED

PART 6 EXAMPLES

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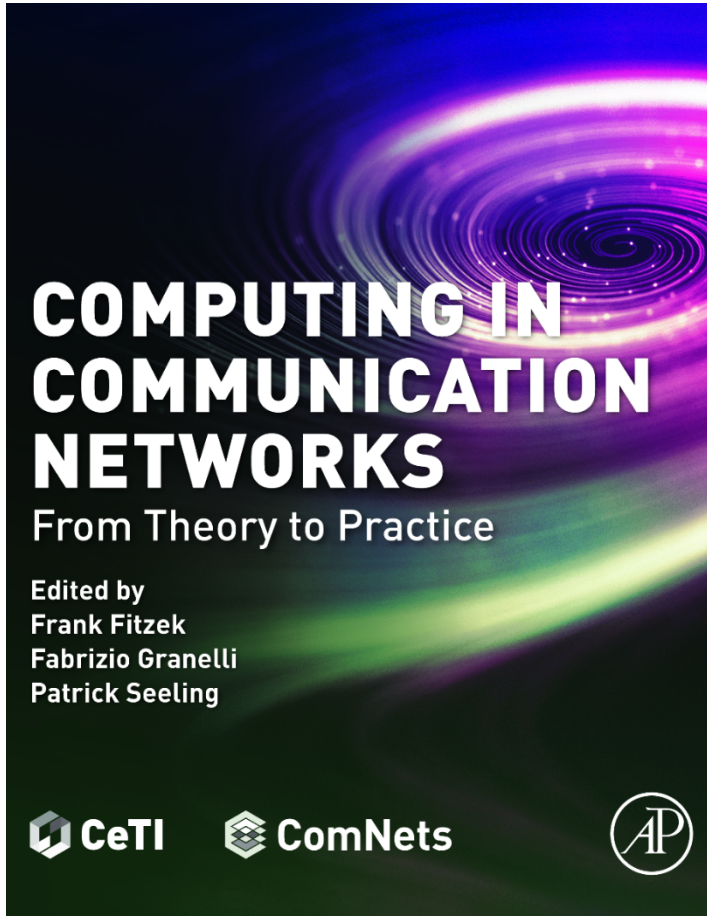
- 15. Realizing Mobile Edge Cloud
- 16. Machine Learning for Routing
- 17. Machine Learning for Flow Compression
- 18. Machine Learning for Congestion Control
- 19. Machine Learning for Object Detection
- 20. Network Coding for Transport
- 21. Network Coding for Storage
- 22. In-Network Compressed Sensing
- 23. Security for Mobile Edge Cloud

PART 7 EXTENSIONS

PART 8 TOOLS



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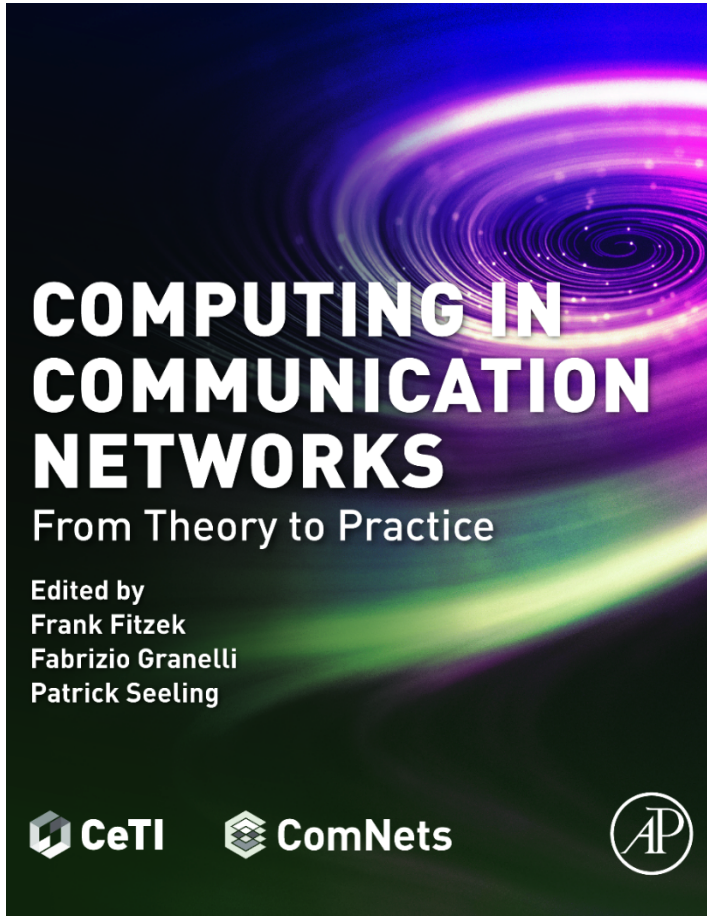
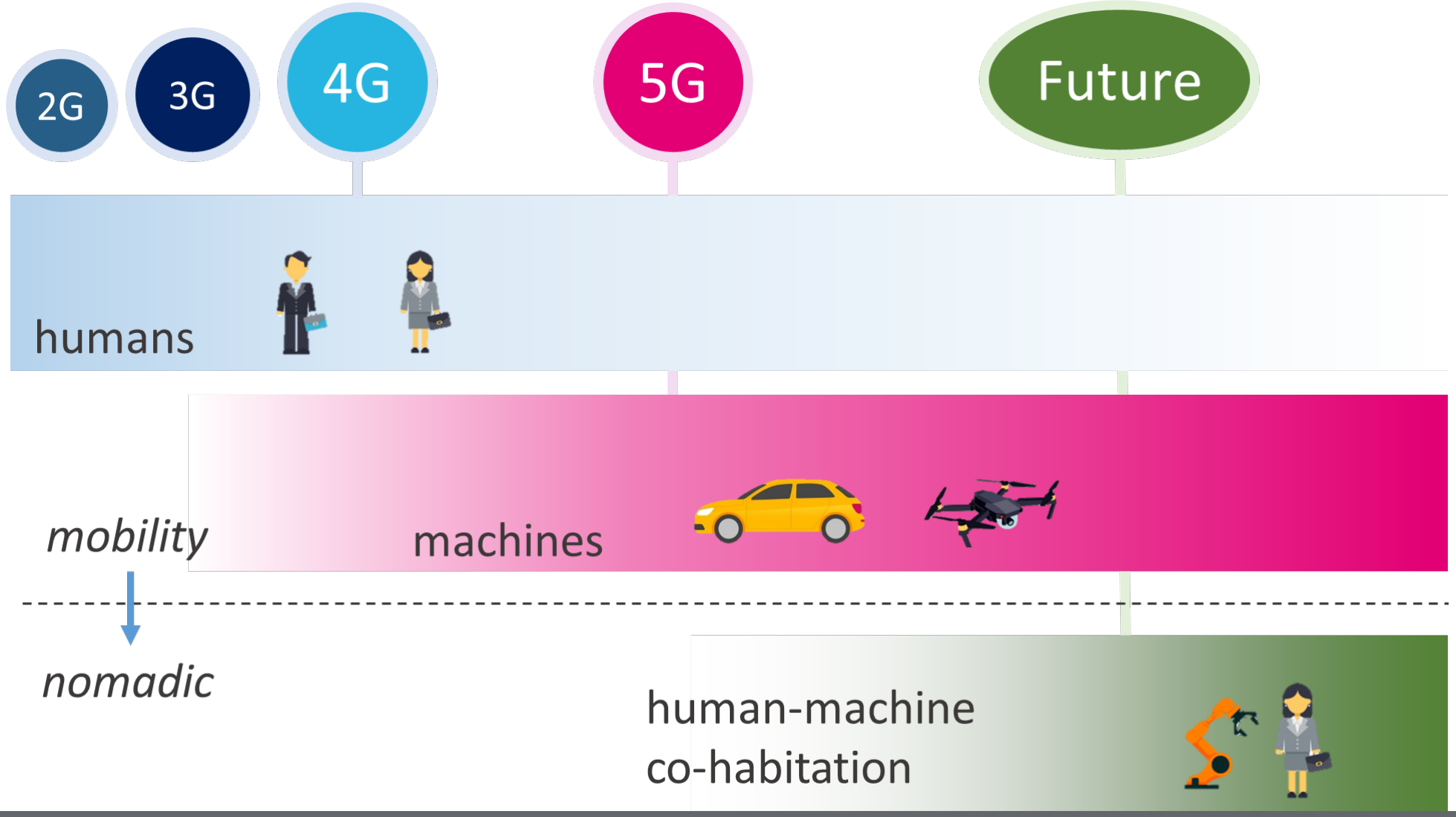
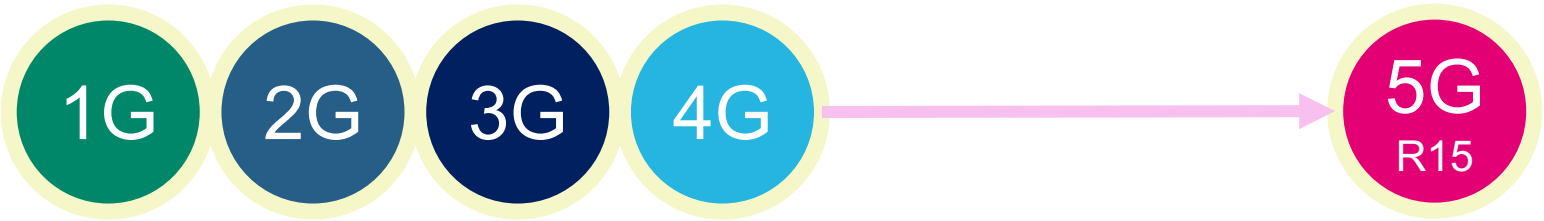


Future of Communication Networks

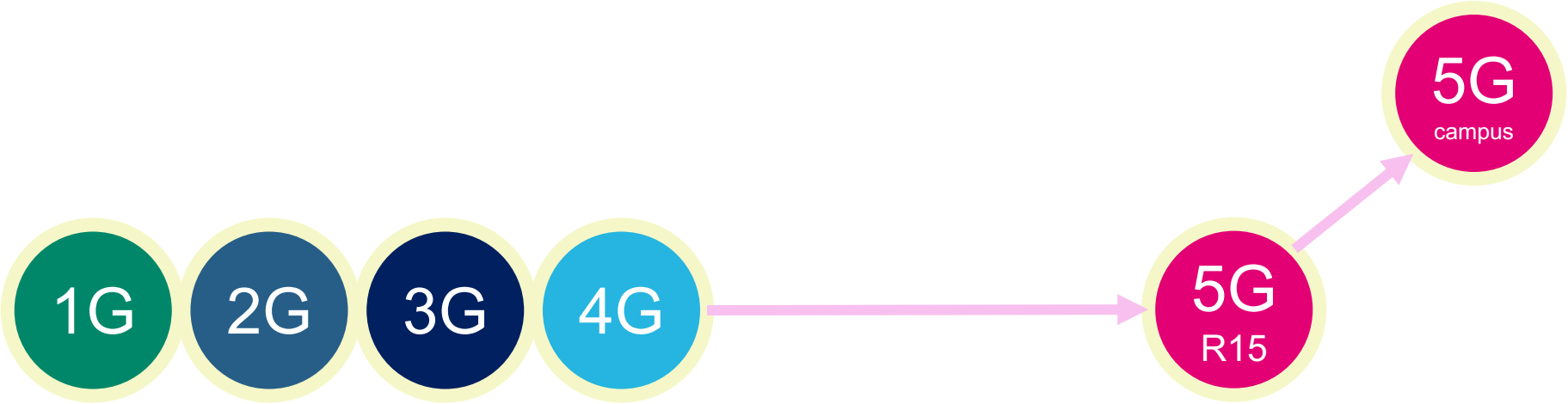
Outlook


2G
3G
4G
5G
Future
humans
mobility
machines
nomadic
human-machine
co-habitation

Outlook



Outlook



5G Campus (BMBF)

TECHNISCHE UNIVERSITÄT DRESDEN

DE CIX

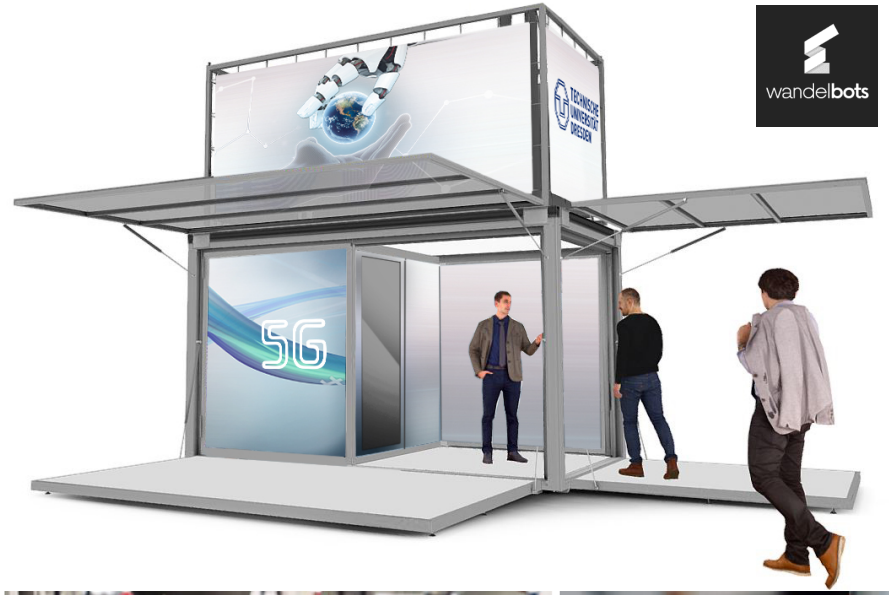
SAP

Deutsche Funkturm

Telemotive
a company of Magna

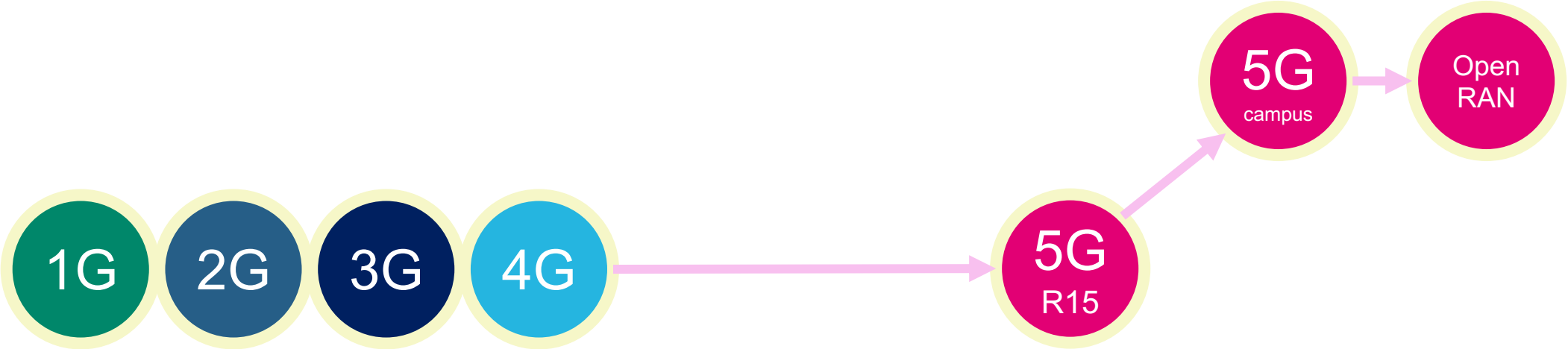
wandelbots

5G Campus (BMBF)

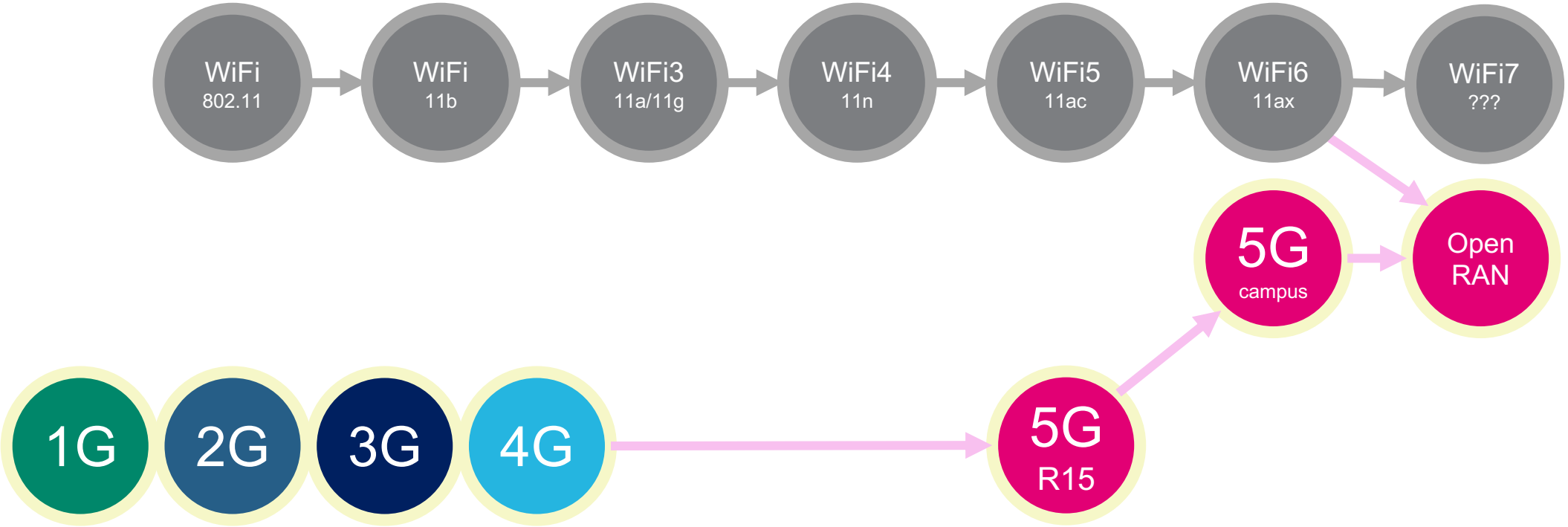


5G Campus (BMBF)

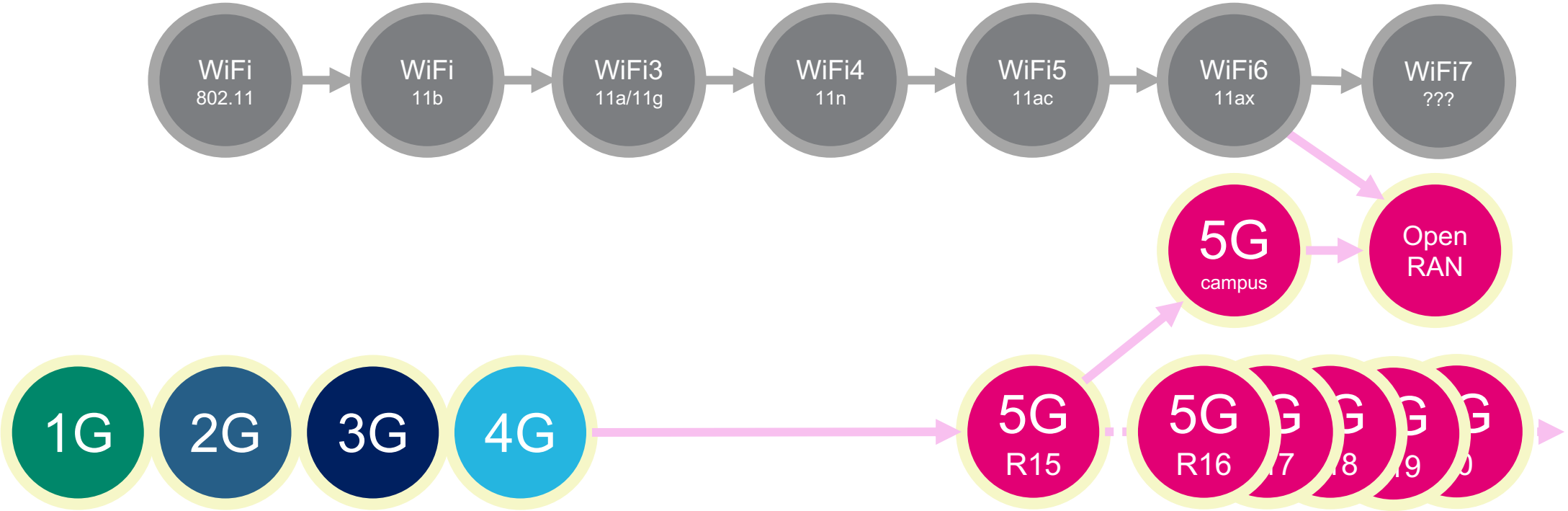
Outlook



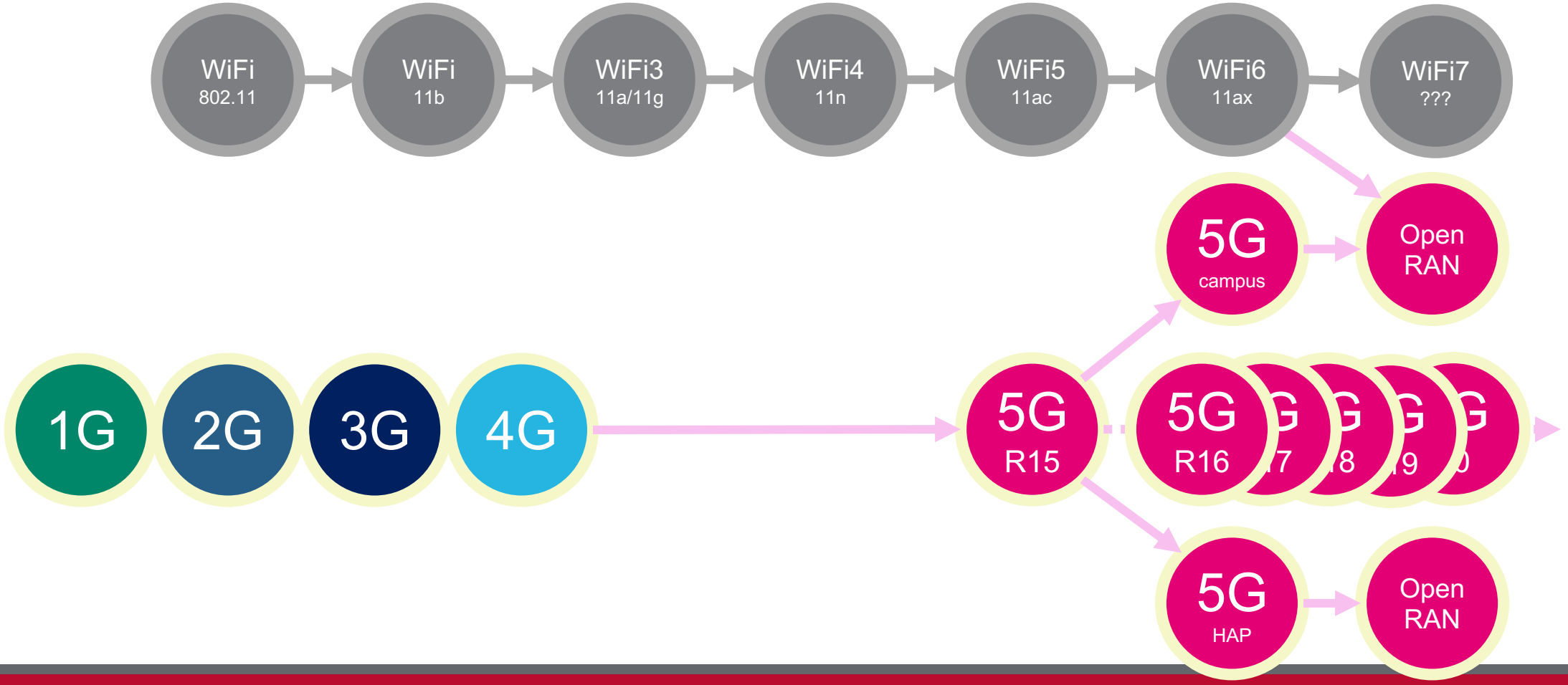
Outlook


WiFi
802.11
WiFi
11b
WiFi3
11a/11g
WiFi4
11n
WiFi5
11ac
WiFi6
11ax
WiFi7
???
5G
campus
Open
RAN
1G
2G
3G
4G
5G
R15

Outlook


WiFi
802.11
WiFi
11b
WiFi3
11a/11g
WiFi4
11n
WiFi5
11ac
WiFi6
11ax
WiFi7
???
5G
campus
Open
RAN
1G
2G
3G
4G
5G
R15
5G
R16

Outlook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11a/11g
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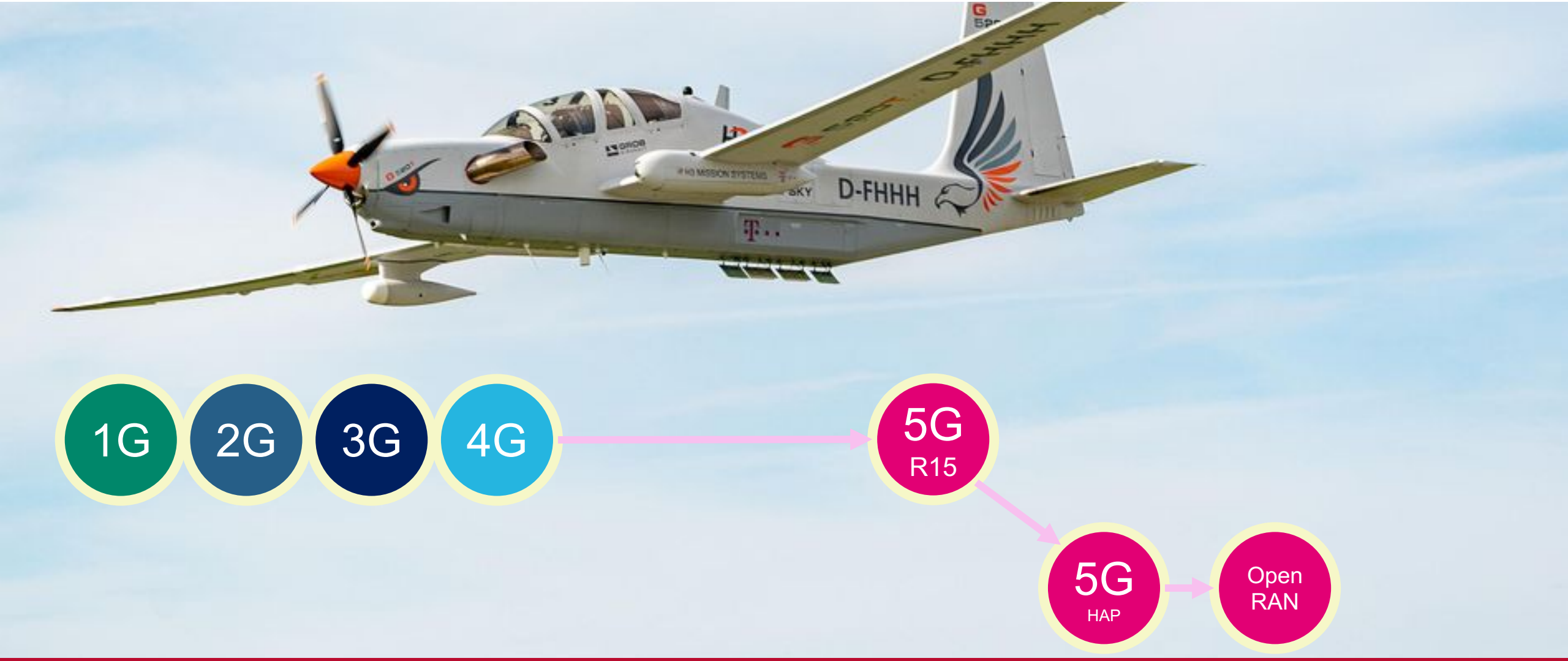
11ac
WiFi6
11ax
WiFi7
???
5G
campus
Open
RAN
1G
2G
3G
4G
5G
R15
5G
R16
5G
HAP
Open
RAN

High Altitude Platforms



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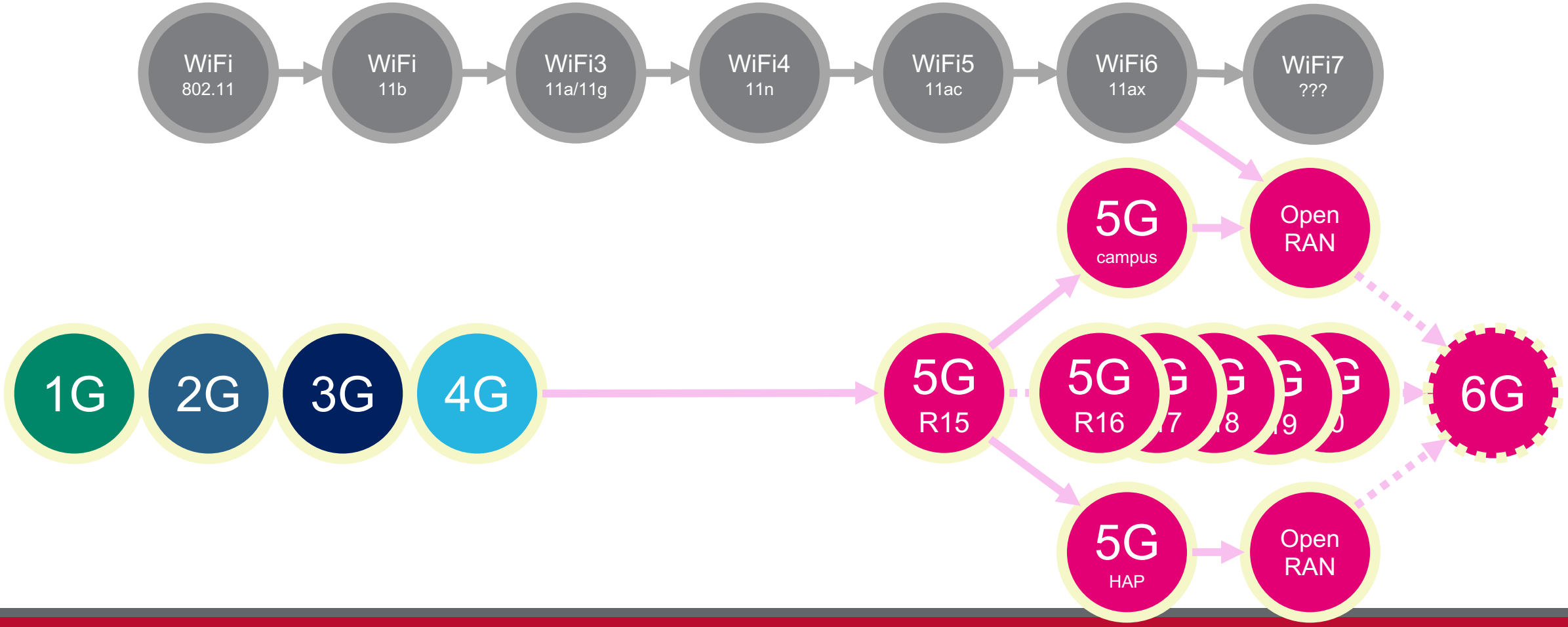
WiFi
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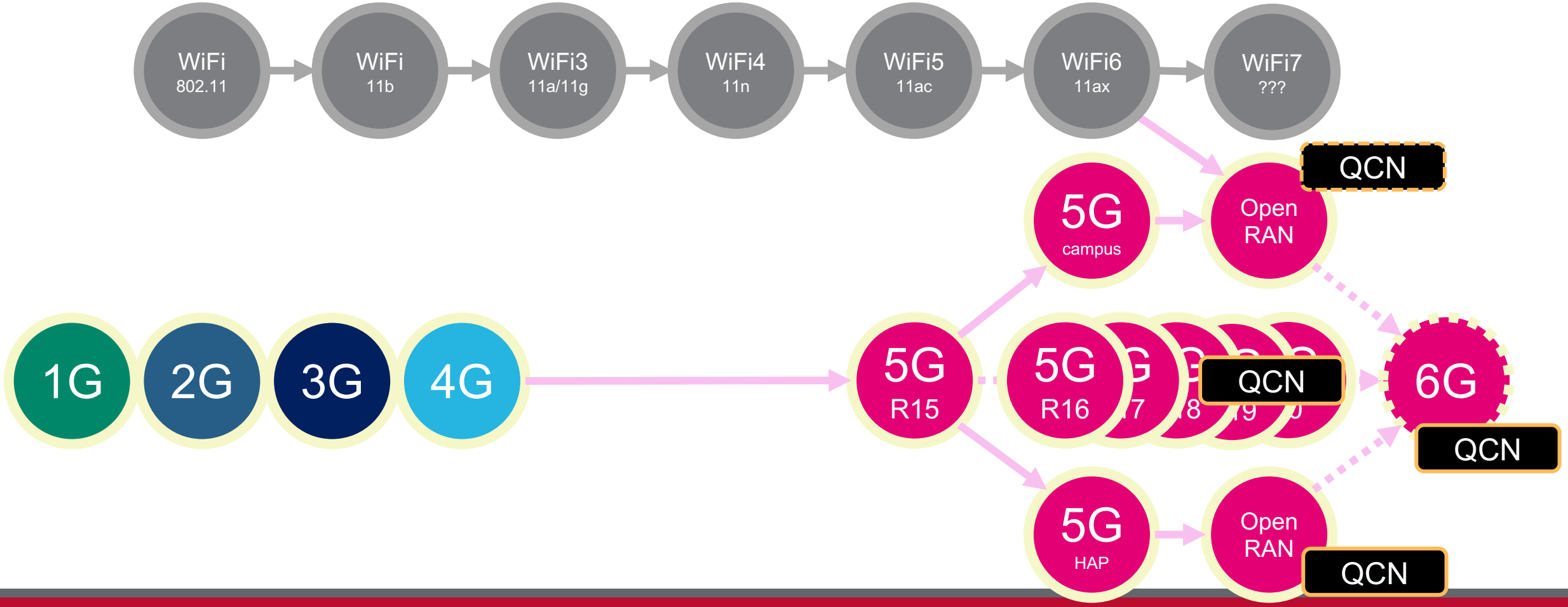
Outlook


WiFi
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